THE EVOLUTION OF INTELLIGENCE

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ABSTRACT

The hypothesis put forward in this thesis is that intelligent behaviour is demonstrable in animals who are actively involved in the selection of significant information which is used to 'decide' on a course of action appropriate in the situation. It is further postulated that the evolution of this capacity is inevitable, given an input system capable of detecting a substantial portion of the vast amount of information inherent in the environment. The inductive nature of the active selection process is expressed in two different cognitive processes. The first, considered to be slower and less flexible than the other, is basically analytic in nature. The inductive nature of the process is expressed in the selection of elemental features assumed to define perceptual and conceptual categories and in the formation of 'rules' for the combination of those features. The second cognitive process is more flexible. Stimuli are classified on the basis of perceived similarity, and representations may be holistic in nature. The nature of the inductive process is expressed in the selection of significant information in the form of elemental features and configurations of elements. A greater ability for induction is required here because of the probabilistic nature of the categorization process. It is suggested that animals are classifiable into three categories, according to whether they only exhibit a passive (non-inductive) process of stimulus classification, the

first cognitive process, or both cognitive processes. Where both processes are present, it is considered that the flexibility of the system allows a greater potential for intelligent behaviour than is possible in a system using only the first cognitive process.

CHAPTER 1

INTRODUCTION

The year 1859 was an epochal one for humanity. In that year, the distinction between human and animal became less clear. But although the basic idea of evolution is now commonly accepted, the fight to maintain human superiority has continued unabated. In spite of accumulating evidence against human uniqueness this assumption still underlies much thinking in social science.

Today, the evidence is indisputable that humans, gorillas and chimpanzees share 99% of their DNA. The separation of the human line and that of the apes almost certainly occurred only 4.5 million years ago (Gribbin & Cherfas, 1982). As scientists delve deeper into the molecular structure of animal life, the distinction between humans and other animals becomes increasingly hard to see.

Accordingly, many instead try to find human uniqueness at the more gross, behavioural level. Yet it seems that here too, there is no ready answer. Man as the only tool-using animal is a myth that has long since been destroyed. Language has always enjoyed considerable popularity, but it seems that the meaning of 'language' as something unique to humans has had to become increasingly restricted as examples of complex language abilities are demonstrated in other animals.

Of course, it has always been popular to assume that it was 'intelligence' which separates human and non-human

animals. To some extent this is a self-fulfilling prophecy, since it seems that the meaning of intelligence is rooted in the assumption that intelligence consists of those cognitive abilities which distinguish humankind. Even among those who purport to look for intelligence among non-human animals it is common to redefine 'intelligence' when it relates to non-humans in a way that makes no explicit reference to cognitive processes. Thus, there seems to be a common assumption that, if one may talk about non-human animals being intelligent, then it is a different sort of intelligence than that evidenced by humans.

This appears to be an assumption unsupported by any 'hard' evidence. It particularly seems unwarranted when one considers that the nature of human intelligence is a question that still lacks a wholly satisfactory answer. To then assume that it is nevertheless unique, of a different order than animal intelligence, appears little more than anthropocentric bias.

It is common today to talk about biological organisms as information-processing systems. Indeed, it is in terms of information-processing systems that we may view the evolution of life on this planet. As J.Z. Young says,

"...every form of life...can continue to meet the demands of its varying environment if it shows adequate variety of actions and sufficient capacity to collect the information needed to act correctly. Each individual is able to do this by virtue of its particular range of sensory and motor capacities...The pressure to acquire better sources of information and ways to adapt is thus itself a factor making for change...New means of coping with the environment

appear, involving greater complexity of organisation... This increase of information as to how to survive is the main sense in which there has been progress during evolution." (Young, 1981).

It is in the terms of the development of increasingly complex information-processing systems, that the evolution of intelligent behaviour is considered here.

Information processing systems may be looked at in terms of structure, process and knowledge (Hunt, 1980). The structural aspect concerns mechanistic capacities for storing, retrieving and transforming information. The application of these capacities in a particular and possibly highly flexible order, is the process aspect. The knowledge aspect concerns the co-ordination of the present situation with stored information. Although both structure and knowledge clearly play an important role in determining the capabilities of the system, it is in the processing of the information - in the way in which raw data are integrated, classified and acted on - that the essence of intelligence lies. The evolution of intelligent behaviour is the evolution of processing methods.

To justify this assertion, it is necessary to investigate research from several fields. We will start with a discussion of what is meant by 'intelligence' and from there investigate the processes of human categorization. Although it is commonly assumed that the processes of perceptual and conceptual categorization are the same, it is clear that the nature of the human information-processing system is not wholly explicable by cognitive theory. Accordingly we must consider other levels of processing in humans. This information, together with cognitive

theory, allows us to consider a model of information processing which involves two fundamentally different cognitive processes. Studies of non-human animals provide the basis for a theory of how these processes evolved.

CHAPTER 2

THE EVALUATION OF INTELLIGENT BEHAVIOUR

2.1 IDEAS ON THE NATURE OF INTELLIGENCE

What is understood by 'intelligence' is to a large extent a matter of definition. In common speech, it refers to the "ability to understand, reason and perceive; quickness in learning, mental alertness; ability to grasp relationships" (The Penguin English Dictionary). Traditionally, researchers in the field of human intelligence have attempted to more rigorously define the nature of intelligence by establishing those 'mental faculties' which presumably allow a person to demonstrate these abilities. Intelligence is thus seen as an attribute, or cluster of attributes, that is possessed in greater or lesser measure by individual humans. The principal issues within this approach have concerned the questions of (a) whether there is one 'general intelligence' property or a number of related problem-solving properties, and (b) the relative importance of genes and experience in determining the level of intelligence.

The application of this viewpoint to the more general question of intelligence among animal species (note: 'animal' used unqualified always includes humans) - in particular, the question of whether intelligence is demonstrated by animals other than human - has resulted in an emphasis on artificial problem-solving tests in experimental studies. Another approach to intelligence however, has become increasingly popular in ethological research.

In this approach, one talks not of the 'disposition' of intelligence, but of the description of behaviour as intelligent. From this comes a conceptualisation of intelligence as an abstract characterization of the organism's behavioural responses to pressures from the environment (Hodos, 1982). To quote Tuddenham: "intelligence is not an entity, nor even a dimension in a person, but rather an evaluation of a behaviour sequence (or the average of many such), from the point of view of its adaptive adequacy. What constitutes intelligence depends upon what the situation demands.." (Tuddenham, 1963). We see this echoed in Jerison's (1973) description of intelligence as "plasticity in the face of a changing environment", and Bindra's (1976) definition of intelligent behaviour as "more purposive than haphazard, more intentional than accidental, and more foresightful and innovative than impulsive and stereotyped".

This approach emphasises the observable characteristics of intelligent behaviour. It is no doubt considered by most ethologists that the 'cognitive' processes which may be presumed to underlie this behaviour, are simply not their concern. It is, however, the concern of this thesis, which takes a cognitive approach to the question of the evolution of intelligent behaviour. Thus, the writer follows the ethologists' view as regards the observable characteristics of intelligent behaviour, but looks to the 'common-sense' view of the nature of intelligence for pointers to the underlying cognitive processes.

2.2 THE 'COMMON SENSE' VIEW OF INTELLIGENT BEHAVIOUR

The behaviour of bringing plant material home for the

purpose of growing fungi (a food of which you are particularly fond); of carefully tending it, putting fertiliser on it, keeping it free of moulds - would you describe this behaviour as intelligent?

The evaluation of behaviour as intelligent is often a function of the assumptions made about the organism involved. The behaviour described above could easily have been carried out by a human, and if you knew (or assumed) that this was in fact the case, you would have no hesitation in so evaluating it. However, if the writer informed you that the behaviour described was in fact a characteristic behaviour of the leaf-cutting ant, you would probably be equally certain that the behaviour was not intelligent. Why? Probably part of the reason is an anthropomorphic bias; but there are also important assumptions being made about the events underlying the behaviour. If a man behaves like this, there is a tendency to ascribe all sorts of qualities to the action - qualities involving purposiveness, judgement, choice, the ability to predict the consequences of his actions. On the other hand, we are reluctant to ascribe these qualities to an ant. In this case quite rightly, for despite the complexity of the behaviour, it can be clearly shown to be highly stereotyped, and dependent on simple orienting responses to key stimuli.

An equally complex behaviour of quite a different order is exhibited by the female sand wasp. Before laying her eggs, she digs a burrow, covers the entrance, catches a caterpillar, brings the dead caterpillar back to the burrow, opens the entrance, takes the caterpillar to the chamber she has built at the bottom, and then lays her egg on the caterpillar. She then leaves, seals the entrance, and does it all over again in

another place (each wasp simultaneously cares for 2 or 3 nests). A few days later, she returns to each of her nests to inspect them. If necessary, she then brings the larva one to four caterpillars (as appropriate). The process is repeated once more before the wasp tightly seals her burrow.

It seems clear that learning is involved here. However, the flexibility of this behaviour is quite limited. Baerends & Baerends (in a study reported by Tinbergen, 1968) found that although the wasp could adapt her behaviour (as regards the number of caterpillars brought to her nest) according to (a) the number of caterpillars in the nest when inspected; and (b) the size of the larva when inspected, she did not modify her behaviour if these factors were altered when she returned with the prey. Here it seems, is an example of "a complex interaction between instinct and learning in (which) the insect is "instinctively set" to encode and process complex, but precisely limited, bits of information" (Denny, 1980). It is the limits which would seem to preclude evaluating the behaviour as intelligent.

These two examples demonstrate that complexity of behaviour is not a sufficient reason for the ascription of intelligence. Complex behaviour patterns may be built up from stereotyped motor responses to specific sensory stimuli (as with the leaf-cutting ant), and from the interaction of 'instinctive' components with limited learning abilities (a borderline case, which we are nevertheless reluctant to term 'intelligent'). A more formal study which was specifically designed to answer the question of whether a particular behaviour could be classed as 'intelligent', was carried out by Charles Darwin on earthworms (Darwin, 1904; reviewed by Reed, 1982).

The behaviour selected by Darwin for study was that of lining a burrow with leaves. Darwin observed that the earthworms typically grasped a leaf by its tip in order to pull it into the burrow. In general, this is in fact the best way of pulling a leaf into a worm's burrow. To demonstrate whether this behaviour was intelligent or not, he ran a number of tests which were designed to examine the flexibility of the behaviour in responses to changing environmental factors. Specifically, he looked at three possible 'explanations' which he considered to be the alternatives to naming the behaviour 'intelligent': "instinct", "habit" and "trial-and-error". Of these, "instinct" is the most important, because it is commonly regarded as the antithesis of intelligence. It is worth noting therefore, three predictions Darwin made concerning instincts:

(i) instincts are relatively invariant across a population, or across a sexual group within a population;

(ii) instinctive behaviour might occur with little or no individual experience; and

(iii) instinctive behaviour will be relatively inflexible with regards to changing environmental conditions.

To test the flexibility of the behaviour with regard to changing environmental conditions, Darwin first ascertained that one of the adaptive values of burrow linings is temperature control, and then observed the behaviour under various temperature regimes. Results indicated that the leaf-pulling behaviour varied in appropriate ways with the alterations in temperature, where the most appropriate way is the one which results in the least cool air entering the burrow (in accordance with the predetermined 'purpose' of the behaviour). Where environ-

mental conditions were such that burrow linings were unnecessary for warmth, far less selectivity as regards what area of the leaf was grasped, was demonstrated.

Further tests of the flexibility of this behaviour involved changing the stimulus - that is, the type of leaf. Using rhododendron leaves (which, unusually, tend to be narrower at the base than at the tip), it was found that worms pulled them by the base 66% of the time - a figure which compares almost precisely with Darwin's assessment of the proportion of leaves which would have gone in most easily by the base. (Note: Darwin regarded this as a test of whether the action was 'habitual', but the distinction between an 'habitual' and an 'instinctive' behaviour is not one that is clear to the writer, and accordingly the question of 'habit' has been subsumed under that of 'instinct'.)

To test whether some innate avoidance response to a specific cue (namely, that of 'points') was underlying this behaviour, Darwin used pine leaves as test stimuli. He found that when the points of the needles were removed, the worms still pulled the leaves by the base. This was true even when the two ends (pine leaves consist of two leaves joined at the base) were fastened together so that they could be pulled by the 'tip' of the leaf. From this, Darwin concluded that the behaviour was not an avoidance response to a specific cue (please note that the question of the adequacy of the tests with regard to Darwin's conclusions is not a point at issue here).

Finally, Darwin investigated whether this behaviour could be explained in terms of trial and error. Using paper triangles which display by dirt and crease marks any attempts to pull them by areas other than the apex, it was found that in

less than 10% of the cases were the triangles grabbed first at some other locale - thus ruling out trial and error.

The major points to note from Darwin's study are that:

(i) he considered that the first requirement for an evaluation of behaviour as intelligent was to determine the adaptive significance of the behaviour;

(ii) from this, the most appropriate way of carrying out the task was determined;

(iii) the behaviour was observed in order to determine whether it was appropriate;

(iv) the possibility of the animal happening on the most appropriate way by following instinct was examined step-by-step, by investigating (a) whether the behaviour varied as the changes in setting altered what was the most appropriate way of carrying out the task; (b) whether the behaviour resulted from an instinct relating to specific 'key stimuli'; and (c) whether the behaviour resulted from a process of trial-and-error; and

(v) Darwin considered that the results of his experimental study implied the involvement of attention, discrimination, choice and judgement in the earthworms' behaviour, and that this justified its evaluation as intelligent.

It would seem then, that behaviour may be evaluated as intelligent when it has been shown to vary appropriately with changes in the environment such that the most appropriate way of carrying out the task is changed, where appropriateness is determined in light of the adaptive significance of the behaviour, and where the behaviour can be shown to be directed towards achieving some specific goal. This last requirement

refers to the apparent need for qualities such as purposiveness, judgement, choice, and the ability to predict the consequences of one's actions, to be involved in the behaviour (if it is to be evaluated as intelligent). That this is a required characteristic of intelligent behaviour may not yet be evident. The 'proof' of this assertion can only come from consideration of behaviours which we intuitively assess as 'intelligent' or 'non-intelligent' - after all, it must be remembered that what intelligence is, is to a large extent definitional, hence unprovable.

Homing behaviour is a good example because the objective of the behaviour is clear. It is also a behaviour which is demonstrated in a number of disparate types of animal, and shows an equally variable method of performance.

In general, we can say that homing behaviours can fall into three categories:

(i) it could depend on an internalized memory of the route or of a sequence of physical or chemical cues along numerous routes home;

(ii) it could involve following a slime trail, chemical gradient, physical path etc; and

(iii) it could result from no more than natural restrictions of topography.

Now it seems unlikely that the last two categories could involve intelligent behaviour. The first category however, is worthy of closer study. While the precise mechanisms involved are far from fully understood, it is clear that some animals use visual landmarks in finding their way home. Can we say that this constitutes intelligent behaviour? The question arises - how does the recognition of such objects differ

from the use of, say, slime trails? The behaviour described in the second category is similar to the behaviour of male silkmoths in finding their mates. The male silkmoth responds (by vibrating his wings) to contact with molecules of a chemical substance produced by the sex organs of a ripe female. The moth orients to the wind direction, and keeps flying into the wind for as long as he receives the stimulus input. In other words, the behaviour is a simple response to stimuli which trigger receptors designed specifically to respond to that type of stimulus. The difference between that type of response and a response to a visual landmark would appear to chiefly reside in two factors: the nature of the stimulus; and the use of memory and learning.

It would seem evident that environmental landmarks (essentially temporary in nature) could hardly form part of an animal's genetic inheritance - they must be learned. And indeed, it has been demonstrated that ducks and geese, for example, transmit such information from generation to generation (Young, 1981).

If then, such behaviour involves learning and memory, does this necessitate it being called intelligent? Although we tend to regard learning and memory as necessary for intelligent behaviour, we are still reluctant to name behaviour as intelligent merely on the evidence that such phenomena are involved (witness the sand wasp). Something more is needed, to do with our terms "reason", "judgement", "choice". What is it that we are basing our (largely intuitive) notion of intelligent behaviour on?

2.3 THE UNACKNOWLEDGED ASSUMPTION

It has been common to assume that 'lower' animals 'discriminate' while humans 'conceptualise' or 'abstract'. The difference in terminology makes apriori assumptions concerning the respective mental capacities of animals and humans, but is there in fact a behavioural distinction? What does it mean to 'abstract'? The term indicates a process of taking something out; the implication is that humans categorise objects by picking out specific features or attributes of the object and comparing them with some 'concept' (which may be a list of attributes or a network of elements in specified relationship, or something else) stored by the organism. To 'discriminate', on the other hand, simply means to act on the basis of there being a difference between two or more objects (note: the verb is also often used to refer to the process underlying the behaviour, but here it shall be used only in its former meaning). It is clear that the word involves no assumptions about what is involved at a cognitive level.

This difference in terminology appears to reflect the common and long-standing belief that the essential characteristic distinguishing human from other animal species is intelligence. The rationale for the distinction however, would appear to be found in the perception of a difference in the complexity of human and non-human information-processing systems. That is, the justification for the distinction is found in the assumption that humans use an active process in selecting relevant information, while other animals use a passive process. (Please note that it is not the writer's contention that this assumption is justified, nor that it is

one held by all researchers - merely that it seems to be the only way to make sense of the different approaches to human and non-human processing systems.)

This point may be clarified by consideration of the concepts of 'top-down' and 'bottom-up' processing. Bottom-up, or data-driven, processing is a reductionist concept - detectors identify features, features combine to form patterns; patterns combine to form more complex concepts. On the other hand, top-down or conceptually driven processing, involves the perceiver more actively in the process, by imposing its own knowledge and conceptual structures on the signals being received from the environment. It seems clear (see Anderson, 1980), that the amount of processing required in a pure bottom-up system, and the 'noisiness' and unreliability of sensory signals, necessitates some top-down processing (given a system capable of detecting a significant amount of the vast array of sensory data inherent in the environment).

Thus, the fine discrimination of which a human is capable clearly requires a sensory system capable of detecting, and discriminating between, a vast number of stimuli, and this requires a more active selection process than is explicit in bottom-up, feature-detector approach.

That is, it is contended that what is understood by the term 'intelligence' is partly a result of the belief that it is an attribute of humans rather than animals in general, and that its essence lies in the assumption that humans have choices in their course of action, and their selection of the appropriate behaviour is in some way different from that demonstrated in non-human species. The writer is forced to conclude that this difference lies in some assumed distinction

of an 'active' vs a 'passive' process. The nature of this active process is discussed in the next chapter.

2.4 SUMMARY

It has been said that the ascription of intelligence to specific behaviours is determined partly by the flexibility and appropriateness of the behaviour, and partly by the judgement that (a) the behaviour is selected by the organism from a number of courses of action that are equally possible, and (b) this choice is based on the organism's judgement that it is the most adaptive response available in the circumstances. It has been contended that the level of appropriate variability needed for an evaluation of behaviour as intelligent, requires a considerable amount of information to be processed by the organism - information which includes that previously acquired, as well as that inherent in the situation - and that the processing of such an amount of information requires the active selection of significant information. Hence the conclusion that the (unrecognized) basis for the ascription of intelligence to behaviour, is the judgement that the organism is actively selecting the body of information (stored and situational) which is significant.

CHAPTER 3

CATEGORIZATION PROCESSES IN HUMANS

3.1 INTRODUCTION

This thesis is concerned with the evolution of intelligent behaviour. It has been suggested (in the preceding chapter) that the essential characteristic of intelligent behaviour is the process by which the organism selects what information is significant. This aspect of the information-processing system is clearly a 'cognitive' one, and it is within the context of cognitive theory that a basic distinction in the evolution of intelligent behaviour, is suggested. Although the nature of the selection process is best displayed at lower levels of perceptual processing (the subject of the next chapter), the basic distinction in cognitive processes requires an understanding of the processes by which animals identify and classify complex stimuli.

The objectives of this chapter are:

(i) to provide indirect support for an assumption that the nature of the selection process underlying intelligent behaviour is inductive;

(ii) to outline the theoretical structure of human categorization research, so that we may later discuss examples of animal behaviour within this context;

(iii) to demonstrate the inadequacies of the cognitive models so far postulated;

(iv) to suggest a solution to the problems, and re-examine the models in the light of that solution; and

(v) to construct two 'prototypical' theories which are characterized only by a few general assumptions, and which in their generality will provide the opposing cognitive processes contended to underlie intelligent behaviour.

3.2 THE INDUCTIVE SELECTION PROCESS

3.2.1 The Nature of the Active Selection Process

The difference between a passive and an active selection process alluded to in the previous chapter, is not one which can be easily defined. As it stands, the distinction does not appear to be a useful one. Some rather more specific characteristic of the selection process appears to be required. What this might be is suggested by Premack's (1978) distinction between the types of abstractness demonstrated by non-human (or at least non-primate) species and humans: "Although we are inclined to reserve abstraction for more complex relations, 'darker than' and other comparably simple relations are already abstractions...(but) a speech rule and a prototype are forms of abstraction that rely on many exemplars...(while) one could learn to approach the darker side of an object on the basis of one exemplar". That is, as he goes on to say, such simple relational concepts are primitives, not induced like prototypes and rules.

It is the writer's contention that the difference between human and non-human processing systems that is implicit

in the different approaches (referred to in 2.3) lies in this concept of inference or induction. That is, humans infer significant information, while other animals can not. Thus, the nature of intelligence - the unacknowledged assumption which appears to contain the essence of what is meant by 'intelligence' - is the inductive processing of information. Intelligence is the ability to infer what is significant.

It is on the basis of this contention, that the theoretical structure contained within this thesis is constructed. It is the fundamental assumption - thus, in practice unprovable. The justification for it must come from the internal consistency of the theoretical structure which derives from it; from its usefulness; and from its compatibility with other theoretical and empirical research. A very brief review of some of the empirical research which supports the assumption of an active selection process, and is suggestive of inductive processing, is given below.

3.2.2 Empirical Support for an Assumption of Inductive Processing

That perception, in humans at least, is much more than the simple registering of sensory information, is clearly indicated by cases of selective processing failures as a result of brain damage (see, for example, Benson & Greenberg, 1969). Moreover, a number of studies of visual and auditory information processing indicate the existence of brief sensory stores which hold all the information in the visual or auditory displays, and from which the information for further processing is selected (see Anderson, 1980 for a review of this evidence). It is clear that attention plays

an important role in selecting this information, and that the selection of what to attend to, is partly determined by what features of the situation are considered significant by the perceiver - in particular, by the nature of the task (see, for example, Moray, 1959).

Furthermore, it is clear that contextual information is important, not only in determining what information is significant, but also in the accurate recognition of complex stimuli, such as speech (see, for example, Miller & Nicely, 1955). It seems evident that, even if it is conceded that any pattern is conclusively identifiable by reference to its features, in many circumstances only some of its features will be identifiable, thus requiring the perceiver to use contextual cues in identifying the pattern. However, consideration of complex stimuli such as letters (and it is worth noting in passing that the complexity of letters lies in their use and meaningfulness, rather than their appearance) makes it clear that contextual information is often necessary for accurate identification even when all the features are readily perceptible.

The role of attention and the importance of contextual information, are suggestive of a process of induction; but the principal justification for the assumption - apart from theoretical considerations - is found in the evidence that task variables partly determine what information is considered significant.

3.3 REVIEW OF HUMAN CATEGORIZATION THEORIES

The majority of theories of categorization can be considered to fall into one of three types (or mixture of

these): the classical definitional approach, the probabilistic view, and the exemplar view. (Note: classification of categorization models varies among researchers; I am here following Smith & Medin, 1981.) Discussion of these theories will be in the context of this classification.

A glossary of the more important terms common in this research can be found at the end of this chapter. It should be noted that use of some of these terms is not wholly consistent among researchers, and the specific meaning of a term in the context of this discussion is explained in this glossary.

3.3.1 The Classical or Definitional Approach

The definitional approach has its roots in British empirical psychology - in the belief that a human starts life with a blank mind and associations between stimuli are formed entirely arbitrarily by experience. From this come three properties of categories assumed in this approach:

(i) arbitrariness of category formation;

(ii) equivalence of category members (i.e. each member of a category is equally representative of that category); and

(iii) determinacy of category boundaries (i.e. the distinction between one category and any others is clear-cut).

The second fundamental assumption of importance which underlies the definitional approach, is that concerning the nature of processing systems - that they are hierarchical and analytic. More specifically, as it relates to categorization, it is assumed that categories are ultimately defined in terms of elemental features, which are independently processed,

and to which single units within the processing system are responsive.

The essential characteristics of the definitional approach are that a concept is represented by a summary description of the category, which applies to all members, but which need not correspond to any specific instance. This summary description is composed of a set of features, each of which is singly necessary and jointly sufficient, and a set of rules for their combination. Thus membership in a category is all-or-none. A concept's defining features are assumed to be nested in superordinate categories, thus forming a hierarchy.

(a) Criticisms of the Definitional Approach

Consequent upon the belief that membership in a category is determined on the basis of singly necessary and jointly sufficient defining features, it follows that no exemplar of a concept should be more representative of that concept than any other, and that boundaries between categories should be clear-cut.

Much of the claim against the definitional view comes from the considerable body of experimental evidence for graded responses to category members - evidence that people judge items as being more or less typical or representative of a category; that they judge more typical items more accurately; and that they classify them faster. There is also good evidence that children learn typical exemplars before atypical ones, and when retrieving category members, people assess typical instances before atypical ones (Mervis & Rosch, 1981).

The assumption of clear-cut category boundaries is also

challenged by experimental evidence. Not only are people often uncertain about which category certain objects belong to, but there are often disagreements regarding category judgements between subjects as well as within subjects across time and/or context.

When people are asked to list attributes of exemplars, they mostly list properties that are not true of all the exemplars in the class, implying that non-necessary properties are being used to determine category membership (moreover the attributes listed are also highly correlated with typicality). This problem reflects what is perhaps the most telling argument against definitional theory, namely that, despite decades of searching, researchers have totally failed to come up with a set of defining features for most object categories.

Finally, the classical view assumes a nesting of concepts such that a specific concept (e.g. 'dog') includes all the properties of its superordinate (e.g. 'mammal'), which in turn includes all the properties of its superordinate (e.g. 'animal'). Thus the specific concept will have more common properties and fewer distinctive ones with its immediate superordinate than its more distant one. It follows from many theories of similarity that the specific concept should always be judged more similar to an immediate superordinate than to a distant one. In practice however, a number of exceptions can be found.

Taken separately, none of these criticisms is a decisive challenge to the definitional approach. Some theorists, for example, argue that the 'fuzziness' of category boundaries results from the nature of cognitive processes and does not

reflect category structure. Moreover, the value of the evidence for member gradedness assumes that if categories were definitional, graded responses would not be recorded. This assumption was recently challenged (Armstrong, Gleitman & Gleitman, 1983) when graded responses were found for categories that have been assumed to be well-defined (for details of this study, see 3.3.4 below). More than one interpretation of these results is possible but, as Martin & Caramazza (1981) note, differences in reaction time might be found for well-defined categories if the component properties varied continuously rather than discretely. It must be conceded that graded responses are at least not conclusive evidence for a probabilistic structure of concepts.

However, the total body of evidence makes a compelling argument against a simple definitional theory of concept description, and the rest of the chapter will concentrate on the alternatives to the definitional approach.

(b) Summary

In the definitional approach, a concept is represented by a summary description, which consists of a set of singly necessary and jointly sufficient component properties. The chief challenge to this view comes from the extensive experimental evidence for the graded representativeness of category members, and the failure to identify defining features for most object categories. Other important evidence against it includes:

(i) evidence for the 'fuzziness' of category boundaries;

(ii) indications that non-necessary component properties are used in determining category membership;

(iii) evidence that children learn more typical exemplars first, and that more typical exemplars are assessed before atypical ones; and

(iv) examples of concepts sharing more properties with a distant superordinate than with the immediate one, (from Mervis & Rosch, 1981).

However, it is possible to argue that graded responses to exemplars of a category are not evidence against the definitional approach; and that the 'fuzziness' of boundaries reflects the processes of categorization rather than the actual structure of the concepts.

3.3.2 The Probabilistic Approach

The probabilisitc view differs from the definitional view in that it assumes that instances of a concept vary in the degree to which they share certain properties, and consequently vary in the degree to which they are representative of the concept. Probabilistic theories have in common the view that a concept is a measure of central tendency (mean or mode, according to dimensional and featural models respectively), and that exemplars of a category vary in the degree to which they are representative of the category.

The movement away from a definitional approach towards a probabilistic one was mediated by the belief that, even if there were defining components, there were no rules for their combination. Thus it is not so much the idea of necessary components (which are allowable within a probabilistic approach, in conjunction with characteristic components) but the requirement of rules, (which are necessitated by an assumption of necessary and sufficient components, if top-down processing

is presumed), that is at the root of the reaction against the classical approach.

Typically, the summary representation that describes the concept in the probabilistic approach, is a list of attributes that are characteristic rather than defining, that is, a property achieves inclusion by having a substantial probability of occurring in instances of the concept. An object is then categorized on the basis of possessing some criterial number of properties, or sum of weighted properties. Thus an object is categorized on the basis of some assessed similarity to the summary representation rather than by applying some definition. Implicit in this view is the assumption that the summary representation is the result of an abstraction process, and is not necessarily realizable as an instance.

From this starting point however, the range of possibilities is wide. One broad distinction that can be made between the various probabilistic models is on the basis of whether the comparison process uses features, dimensions, or holistic patterns (see 3.4.1 for a discussion of these distinctions).

(a) Featural Theories

The essential characteristic of this class of theories is that non-necessary and modal features are accompanied by weights reflecting their combined salience and conditional probability. Thus, the summary representation is assumed to consist of salient features that have a substantial probability of occurring in instances of the concept. This general featural theory is typified by frequency models, of which there are two basic types:

(a) Simple frequency models, which assume a stimulus is assigned to a category on the basis of summing the frequency with which each of the attributes have been associated with each of the categories and selecting the category with the highest sum; or

(b) Relational frequency models, which differ from simple frequency models in that, in addition to recording the frequency with which features are associated with categories, the frequencies with which features are associated together are also recorded.

A considerable body of experimental evidence exists which is taken to support frequency models. The main points are:

(i) evidence that subjects can correctly estimate the relative frequencies of features;

(ii) evidence that they use this information by sampling features with high relative frequency;

(iii) evidence that the frequency score (summation of the component frequencies) provides the basis for classifying stimuli; and

(iv) evidence that the frequency score is used in forming prototypes, (from Kellogg, 1981).

(b) Dimensional Theories

Dimensional theories assume that values along any dimension are used to represent a concept, and, similarly to featural theories, are tagged with weights reflecting conditional probability; each concept is described by the average values of the dimensions (as opposed to the modal features). Most dimensional models also assume that concepts having the same relevant dimensions can be represented as points in multidimensional space.

Examples of dimensional models include:

(a) Prototype-distance models, which assume a stimulus is assigned to a category on the basis of which prototype is closest to the stimulus, where distance is measured by summing the distances along each component dimension, and (in many models) where the distances from the various dimensions are differentially weighted for salience.

(b) Average distance models, which classify stimuli on the basis of which stored pattern has the smallest average distance from the stimulus.

(c) Cue validity models, which classify stimuli on the basis of summing the validity information from the component dimensions and comparing this with learned information regarding which values on individual dimensions are predictive of category membership.

(c) Criticisms of the Probabilistic Approach

The probabilistic approach was tailored to answer the problems which have plagued the classical view, and clearly the theories subsumed under this heading have no trouble accounting for typicality effects, which are readily seen as resulting from the differential similarity of exemplars to the prototype. The use of non-necessary properties is entirely compatible with the notion of characteristic rather than defining features. The inability to determine defining properties is no problem, for they don't exist. And because nothing in principle prevents a concept from sharing more properties with a distant superordinate than with the immediate one, the view is consistent with similarity judgements for nested concepts.

The probabilistic view however, has its own problems. The first and most obvious, is that while probabilistic theories get around the problem of having to find defining features, they are still left with the problem of features themselves. This problem relates to any theory which involves a decompositional approach (as opposed to an holistic one).

No decompositional theory has yet found some way of putting constraints on what features may be posited, if they are not defined in terms of single unit responsivity. With no constraints, "the argument is standard and irrefutable that there's no end to the descriptions that can apply to any one stimulus or to all or some of its parts", (Armstrong, Gleitman & Gleitman, 1983). The value of probabilistic theory is considerably lessened by its failure to specify the basis of the feature set, or even to show some likelihood of the numbers of needed features being less than the numbers of lexical items.

Furthermore, featural theories cannot explain how people know about the range of values a property may have; a degree of allowable latitude must be built into each encoded feature or identification of features would be too discriminatory to be functional in the real world. And while it is clear that certain characteristic features of particular concepts are highly correlated with other features, (e.g. birds are typically small and typically sing, but big birds are unlikely to sing), and evidence suggests that people use knowledge about correlated attributes when categorizing, this is not explained in the context of featural theories. Finally, featural theories have not yet been shown to account for context effects.

The only advantage that dimensional theories have, with regard to these problems, is that continuous representation of component properties allows the representation of the variability permissable to a property.

(d) Summary

The probabilistic approach is characterised by the assumption that a concept is represented by a summary description, which consists of a set of component properties that have a substantial probability of occurring in instances of a concept, and that this concept is a measure of central tendency. Category judgements are thus made on the basis of an object's similarity to the description, not (as in the definitional approach) on the basis of applying some definition.

Probabilistic models may be classified according to whether they use features or dimensions as the component properties of a concept, or whether they use an holistic approach. Although it is clear that holistic processing is used in human cognition (see 4.2.1) holistic models are rare, chiefly because of the difficulties in finding some way to assess the similarity of two objects or patterns without breaking them down (but see 3.4.1 for discussion of this point). Moreover, because holistic models assume a one-to-one relationship between words and concepts, an holistic approach would in theory greatly expand the number of concepts required to be stored.

Consequently, most theories take a decompositional approach. Decompositional probabilistic models fall into two categories - ones which are based on modal features,

and ones based on the mean values of dimensions. Within these categories, models can be further classified according to the method used to assess similarity.

One of the principal criticisms to this approach centres around the lack of constraints on component properties. Because of the failure to account for most object categories in terms of sensory properties, the problem has been to find some set of defining principles which specify what constitutes a component property. Without such principles, the situation results in (a) the number of component properties being no less than the number of concepts would be in an holistic approach; (b) the difference between a concept and a component property being purely one of level of discussion; and (c) concepts/components being defined in terms of themselves.

Other general criticisms of decompositional probabilistic models are that they have failed to account for:

(i) the range of variation allowable to a component property;

(ii) correlation of components; and

(iii) context effects.

The approach has however, satisfactorily accounted for the problems which plagued the definitional approach.

3.3.3 Exemplar Models

The probabilistic and definitional approaches have in common the lack of requirement for any instance of a class to exactly match the stored representation (note: although component properties are singly necessary and jointly sufficient in the definitional approach, instances of a class

will usually have additional components which are irrelevant in judging its category membership). The exemplar approach on the other hand, while agreeing with the claim that concepts need not contain defining features, holds that the representation of a concept consists of separate descriptions of some of its exemplars, and that there is no single representation. Thus exemplar models involve a substantially greater lack of abstraction than is involved in the representations based on either the definitional or the probabilistic views.

Exemplar models can differ from each other in essentials significantly - some permit representations with no specific instances, others do not; in some assessing different exemplars for different stimuli is allowable, while in others it is not. What exemplar models do have in common is the idea that categorization of an object relies on comparisons of that object to known exemplars of the category.

It is clear that the possible methods of assessing similarity mirror those discussed under probabilistic models. However, it is worth noting that the models discussed so far have consistently calculated overall similarity by the sum of similarities for each component property (i.e. additive combination), while another possibility (as in Medin & Schaffer's context model, 1978) is to use the product of similarities (i.e. multiplicative combination).

(a) Comparison with the Probabilistic Approach

Because of the variation among exemplar models and because they, like probabilistic models, have been derived from the assumption that members of a category vary in their similarity to the concept, the distinction between the two classes of theories is not always clear. Following Smith &

Medin (1981) however, we can state that the essential distinction is one of disjunctiveness.

The characteristic of disjunctiveness in fact distinguishes the definitional approach from both probabilistic and exemplar views, in that concepts in the former approach are not at all disjunctive, while in the latter two views they are at least partially disjunctive (note: in a totally disjunctive concept instances need not have any features in common; in a partially disjunctive concept any two instances must share some features). Probabilistic models however, are implicitly disjunctive, while exemplar models are explicitly disjunctive. That is, because there is a single summary representation, the different disjuncts in probabilistic models exist only during the categorization process, while in the exemplar view the disjuncts correspond to the stored exemplars.

Consequent upon this, one may note a further three differences between the approaches, which may be taken as characteristic rather than defining as they are not always true for each model. The first of these concerns the degree of retrieval, in that some exemplar models claim that the same representation is not always retrieved in decisions about category membership. The notion of partial retrieval could however, be included into probabilistic models; indeed, it might allow them to deal with the apparent instability of concepts and help explain some context effects. Secondly, in some exemplar models, all representations are realizable as specific instances, while in the probabilistic approach they are not necessarily so. Thirdly, in the exemplar approach, a property can be part of a representation if it

is characteristic of a single instance, while in the probabilistic view, only component properties with a certain degree of commonality are included.

(b) Criticisms of the Exemplar Approach

There is a considerable amount of experimental evidence for the use of exemplars in category judgements (see, for example, Medin & Schaffer, 1978; Brooks; 1978, and Homa, Sterling & Trepel, 1981). Like the probabilistic approach, the looseness of the exemplar approach enables it to adequately handle the problems of the definitional view. It also has some advantages over the probabilistic approach in that exemplars can carry information regarding the range of values for a property, and the correlations among properties. However, the lack of constraints on what component properties make up a concept or even what constitutes a concept, is even greater than in the probabilistic approach.

Moreover, the representation of a concept by a disjunction of exemplars creates two major problems: the lack of any relationship between different exemplars of a concept; and the implication that when summary information is learned (e.g. when you learn that "all birds lay eggs"), this must be stored separately with each stored exemplar. These problems can be solved however, within the exemplar approach, by the inclusion of some form of summary representation (see, for example, Whitney & Kellas, 1984, for experimental support for the claim that both specific exemplars and summary representations are required for category decisions).

(c) Summary

Exemplar models are characterized by the assumption

that a concept is represented by separate descriptions of some of its exemplars. There is no single summary representation. Methods of assessing the similarity of the object-to-be-categorized to stored exemplars of a category are the same as those possible in a probabilistic model.

While exemplar models handle those issues which are problems to the definitional approach, it tends to share the problems of the probabilistic approach. They can, however, better deal with the issue of the correlations among component properties, and that of the range of values permissable to a component property. On the minus side, there are the problems caused by representing a concept by a disjunction of exemplars, with no summary representation.

3.3.4 Alternative Models

A dual theory hypothesising that concepts are described by both a core description, which relates to the compositional meaning, and an identification procedure, which is an heuristic for picking out exemplars in the real world, has become increasingly popular among cognitive theorists. Many of the experimental results that challenge probabilistic models may be solved by theorising that categories have a classical conceptual core as well as identification procedures which have a probabilistic structure. The study by Armstrong, Gleitman & Gleitman (1983) for example, could be taken as support for the dual theory. In this study, objects from supposedly probabilistic categories (sport, vehicle, fruit, and vegetable), i.e. those for which graded responses have consistently been recorded, were used as stimuli together with examples of categories generally supposed to be well-

defined (odd number, even number, female and plane geometry figure). The authors reported that exemplar rating and reaction time tests showed graded responses for both ill- and well-defined categories. While they suggest that this may mean that graded responses do not directly reflect the structure of concepts, they also acknowledge that the results would support the view that there is an 'identification function' which is used to make a rapid sort of data, and which is probabilistic in structure, and a 'conceptual core' which determines category membership on the basis of necessary and sufficient component properties.

Likewise, the (1981) study by Osherson & Smith, which demonstrated that probabilistic theory could not account for conceptual combination or truth conditions, could be taken as indicating that probabilistic theory is only about a limited aspect of concepts - that conceptual combination and truth conditions of thoughts are tasks for the conceptual core. However, to restrict a probabilistic organisation to only part of the structure of the concept does not answer the theoretical problems which have been discussed as inherent in decompositional probabilistic theories. Nor does restricting the definitional approach to the core of the concept assist much in finding those defining components. Although massive effort has gone into the task (see, for example, Fodor & Katz, 1963; and Katz, 1972; 1977), it now seems likely that even reasonably definitional concepts cannot be made to break down into defining components (see Fodor, Garrett, Walker & Parkes, 1980, for a demonstration that even 'bachelor' is not decomposable).

Another possibility is that of a theory which combines

two of these approaches in a rather different way. Two experimental results - the improvement in classification of novel stimuli in later transfer tests following an increase in the number of exemplars during the learning phase; and the decreasing probability that a new stimulus will be categorized by its similarity to an old stimulus when category size is increased and the transfer test delayed - have been taken as support for the hypothesis that, in the early stages of development, a concept is represented primarily by a few exemplars, but that it becomes increasingly represented by its central tendency (prototype) and range (see Homa, Sterling & Trepel, 1981).

3.4 THE NATURE OF THE 'FEATURE'

3.4.1 The Holistic vs the Decompositional Approach

The holistic approach to categorization centres on the assumption of a one-to-one relationship between words and mental categories, e.g. the word 'dog' is matched with a category 'dog', which is unanalyzable.

The only clearly holistic approach that has been systematically developed is that of a template, which may be summarised as a gestalt, isomorphic to the real world, unanalyzable, and inherently relational.

The main reason for the neglect of this approach can be found in two arguments: (i) that an holistic approach would require an immense amount of unanalyzable concepts to be stored; and (ii) the difficulty in giving a satisfactory account of precisely how the matching of stored pattern to real-world object is done.

In contrast, the essence of decompositional theories

is that they try to limit the set of elementary discriminations required to be stored, by assuming that, e.g. categories such as 'dog' are made up of bundles of simpler categories called features. When the decompositional assumption was first postulated, it was assumed that these elemental features were sensory in nature. However, it has proven impossible in practice to determine a list of purely sensory features which adequately describe any object category (see Miller & Johnson-Laird, 1976, for demonstration of this). Component properties suggested often seem no less complex than the categories they supposedly make up and what is in one context a component property, may in another context be a concept.

This indeed, is the major problem for all the theories discussed. In the definitional approach, the nature of the feature might in principle be clearly defined, but in practise no such features can be identified. In the decompositional probabilistic and exemplar models, the failure to establish adequate constraints on features, and the difficulty in finding features which are significantly simpler than the concepts they supposedly describe, are major inadequacies.

The whole value of the notion of component properties clearly rests in the constraints put on them. Ideally of course, one of the constraints should be that component properties are not themselves decomposable. Failing this however, the set of components should at least reveal many of the relations between concepts (e.g. the use of 'female' as a component makes evident one of the relationships between, say, the concepts of 'girl' and 'cow'). (Note that component-sets which reveal all of the relationships between concepts would be made up of primitive, i.e. non-decomposable,

components). To be useful, components should clearly also have some generality. Finally, and most critically, the components must serve as the inputs for category judgements (this is, after all, implicit in the concept of component properties).

The lack of constraints on the feature sets, and the difficulty in finding features that can be described in terms significantly simpler than the terms they supposedly help define, considerably weakens the argument that holistic systems would require too many stored representations.

However, it seems that these problems are perceived as 'easier' than those found when the assumption of independently processable elemental features is discarded. That is, most researchers seem to prefer these problems to the problem of how stored patterns are compared to real-world objects if they are not analyzable.

3.4.2 The Feature Redefined

It is the writer's contention that the nature of the feature is not properly a question for cognitive theorists, except in so far as they need to understand what it is. But the problem would seem to be a matter for researchers into lower levels of perceptual processing. The evidence from these studies is discussed in the next chapter. At this point, it is necessary to offer a redefinition of feature without justification, in order to note its implications for categorization models.

The redefinition suggested is that a feature is an elemental holistic percept, whose component properties cannot be independently processed and later combined, because such an analytic process would lose significant information.

Because what constitutes a loss of significant information is plainly task-variable, what constitutes a 'feature' is very flexible. In other words, what constitutes a feature is something about which no hard-and-fast rules may be set, but instead is answered empirically, on the basis of the requirements of the information-processing system given the task.

It may appear that there is a lack of constraint on what constitutes a feature that is no better than that apparent in decompositional probabilistic models; that this is not the case is a demonstration that, again, will have to wait for the next chapter. The important point here, is that this redefinition allows features to be configurations of elements.

Thus this redefinition allows the issues of the correlation of components and the importance of contextual information to be answered - at the level of structure not process. It also becomes clear that more complex concepts can be formed from simpler ones, without being predictable from them - because the elemental holistic percept of any concept is a function of what aspects of the configuration of elements can be disregarded without loss of significant information. Thus the nesting concept of the definitional approach is challenged, and explanation offered for the exceptions to the rule that a specific concept is always judged more similar to an immediate superordinate than a distant one. Moreover, the challenge to the probabilistic approach on the basis that it fails to account for the way simple concepts combine to form complex ones, is answered at the level of structure and not process.

3.5 THE 'PROTOTYPICAL' CATEGORISATION MODELS

In summary then, we can point to two fundamentally different approaches in human categorization research (note: I do not suggest that every model possesses all the characteristics of one or other approach as I describe them here; but these appear to be the 'prototypical' views which reflect a very basic distinction in fundamental assumptions being made):

(1) the view that a set of defining features and rules for their combination describes a concept/category; that the relationship between members of a category is found in the arbitrary associations of stimuli occurring in the perceiver's experience; that concepts are nested in a hierarchy such that any subordinate concept is nested within its superordinate; and that the 'elemental features' which are presumed to be isomorphic with single units in the input system (see 4.3.1 for discussion of this point), can be independently processed; and

(2) the view that a concept is described by a set of characteristic features (and possibly some defining features) which are shared in varying degrees by members of a category; that the relationship between category members is found in their perceived similarity; that concepts represent the 'central tendency' of this similarity; that there are no rules for the combination of these features; and that the 'elemental features', presumed to be isomorphic with single units in the input system, can be independently processed.

The shared assumption of these views is that categorization uses stored representations that are constructed using

elemental features which are isomorphic with single units in the input system, and can be independently processed.

The alteration of the second of these two 'prototypical' views in the light of the redefined feature removes this last characteristic, and replaces it with the assumption that features isomorphic with single units in the input system, can be integrally processed. The significance of this alteration for the evolution of intelligent behaviour, and what precisely is meant by it, requires an examination of research at lower levels of perceptual processing.

3.6 SUMMARY

The concern of this chapter has been with models of human categorization. The principal characteristics of these models, and their adequacy in accounting for diverse empirical phenomena are summarised in Tables 1 and 2.

It has been argued that the major problems of existing categorisation models come from the assumption that stored representations consist of features which are ultimately decomposable into elemental features (i.e. those to which single units in the input system are responsive), and which are independently processed. A redefinition of the nature of these features, which does not include the necessity for a feature to be isomorphic with a single unit, and which allows integral processing of features, is thus contended to resolve the major inadequacies of decompositonal probabilistic and exemplar models. The assumption that an inferential selection process underlies intelligent behaviour makes it clear that the formation of concepts requires, at least initially, the use of exemplars. Thus some blending of the two, not

dissimilar, approaches would seem required. With the modifications suggested by the assumption of inductive processing and the redefinition of feature, a general probabilistic process of categorisation is suggested to underlie intelligent behaviour. The classical approach on the other hand, also appears to have a certain validity, and it is suggested that a general definitional process of categorisation is also present in animals capable of intelligent behaviour.

It does not appear that the redefined feature is at all compatible with the definitional approach, but the different natures of the feature for the two approaches is not anomolous. On the contrary, it will be contended that it is in the changing nature of the feature that a greater potential for intelligent behaviour was born.

Table 1: Comparison of the Principal Characteristics of the Three Approaches

Definitional	Probabilistic	Exemplar
single summary representation	single summary representation	no single summary representation
defining features	characteristic features	characteristic features
not necessarily realizable as instance	not necessarily realizable as instance	exemplars realizable as instances
category judgements on basis of whether or not object has defining features	category judgments on basis of assessed similarity to summary representation	category judgements on basis of assessed similarity to stored representation
concepts not disjunctive	concepts implicitly disjunctive	concepts explicitly disjunctive
total retrieval of summary representation	total retrieval of summary representation (but partial retrieval could be included)	partial retrieval of representations
	only components with a criterial degree of probability of occurring included in representation	allows inclusion of components which only occur in one instance

Table 2: Comparison of how the Different Models Account for Various Phenomena of Categorization

Problems:	Defnal.	Probic.*	Exemp.	Dual	Mixed
1. 'fuzziness' of category boundaries	no	yes	yes	yes	yes
2. typicality of category members	no	yes	yes	yes	yes
3. nonnecessary components	no	yes	yes	yes	yes
4. similarity judgements for nested concepts	no	yes	yes	yes	yes
5. disjunctive concepts	no	yes	yes	yes	yes
6. failure to find defining features	no	yes	yes	no	yes
7. lack of constraints on component properties	yes	no	no	no	no
8. correlation of component properties	no	no	yes	no	yes
9. context effects	no	no	yes	no	yes
10. generalization of component properties	no	no	yes	no	yes
11. conceptual combination	yes	no	no	yes	no
12. use of exemplars in category judgements	no	no	yes	no	yes
13. use of frequency scores in category judgements	no	yes	yes	yes	yes

'no' means that this is a problem not accounted for in this model or approach.

'yes' means that this is satisfactorily accounted for.

* This refers only to decompositional probabilistic models.

GLOSSARY OF TERMS

Concept: In the context of this review, the term will simply be used to refer to a mental representation which is used to assign an object to a particular class of objects, and to infer some of the properties which might belong to an instance of a particular class.

Categorization: This will be used simply in the sense of determining that a particular object is a member of a class of objects, with the implication that it is thus associated with the concept that relates to that class.
(Note that the defining of 'concept' and 'categorization' essentially in terms of each other enables 'concepts' and 'categories' to be used interchangeably.)

Definitional Approach: This nomenclature refers to the classical approach to concepts, which assumes that all concepts are well-defined. It is thus in contrast to those views which assume that some exemplars are more representative or typical of the concept than others. It is synonymous with the term 'definitional theories', (see 'defining features', 'probabilistic models', 'exemplar models' and 'well-defined categories').

Probabilistic Models: This term will refer to those models which in main essence differ from the definitional approach in that the summary description of any concept is not restricted to necessary and sufficient conditions, but

represents some measure of central tendency against which instances are judged on the basis of similarity. These models are often called prototype models, but use of the word 'prototype' in this context reflects a definition of the term which is rather too general (see Smith & Medin, 1981). (See 'definitional approach', 'prototype', 'featural theories', 'dimensional theories', 'holistic theories', and 'exemplar models'.)

Exemplar Models: This refers to the class of models which assumes no single summary representation of a concept, but proposes that objects are classified on the basis of comparison with a number of stored exemplars. This is in contrast with the definitional and probabilistic approaches.
(See 'definitional approach', 'probabilistic models', and 'exemplars'.)

Exemplars: I note this term simply to make the point that the common usage of this word in the literature (as meaning one of the object members of a category or instance of a concept), should not be confused with exemplar models.
(See 'exemplar models'.)

Prototype: Because of the degree of variation in the use of this word, the term 'probabilistic' is used in this text to refer to a class of theories often (confusingly) called 'prototype' theories. This usage follows Smith & Medin (1981). When 'prototype' is used in this text, it is taken to mean a summary representation reflecting some measure of central tendency of the instances of the concept, and including the

implication that some category members will consequently be more similar to it than others.
(Also see 'probabilistic models' and 'prototype-distance models'

Features: The usage of this term is one of the most confusing in the literature (the other is 'prototype').. Features are generally used interchangeably with the terms 'attributes' and 'properties'. Following the classical definitional approach to concepts, features often refer only to sensory or perceptual features, but the term usually includes abstract and functional features. More detailed discussion of what constitutes a feature can be found in the text, but (misleadingly) simple definition captures the essence of a feature. A feature is a component property of an object or concept, i.e. one that helps describe a concept but doesn't constitute a complete description, that is in fact used in categorizing an object. One of the principal confusions is that 'feature' is used both in this general sense, and in the more specific sense of a qualitative component. In this latter case, a feature is an all-or-none affair (i.e. it either does or does not exist, with reference to some concept), and is contrasted with a 'dimension'. In this text, 'feature' will be restricted to its more specified meaning; in its general meaning the term 'component' or 'component property' will be used. (Note: this usage of 'feature' is specific to this chapter; elsewhere it will be used in its general sense.)
(See also 'defining features', 'characteristic features', 'dimensions', 'decompositional theories' and 'featural theories'.)

Dimensions: A dimension is a quantitative component; in

contrast to a feature therefore, it expresses component properties in graded terms. The word can be used in a weak sense which allows the possibility of discrete (as well as continuous dimensions. However, it seems more reasonable to insist on the property of 'betweenness', thus disallowing binary-valued dimensions.
(See 'dimensional theories'.)

Decompositional Theories: As a consequence of 'features' being used generally as well as specifically, the term 'decompositional theories', while clearly referring to the basic distinction with holistic theories, is often used interchangeably with 'featural' theories. It does however, refer to the approach which assumes that concepts can be broken down into component properties. It thus subsumes definitional models, most probabilistic models, and most exemplar models. 'Component' theories, also used in the literature, refers to the same thing.
(See 'definitional approach', 'probabilistic models', 'featural theories', and 'exemplar models'.)

Holistic Theories: In the text this is used for a particular subset of probabilistic models. However, this is only because the minimal work on holistic theories of categorization has been done in the context of a probabilistic approach. The distinction in point of fact, is one of holistic theories versus decompositional or component theories, and the essence of the distinction is that the former assume a one-to-one relationship between the mental representation of a concept and the real-world object that is an instance of that concept (the representation to be unanalyzable).
(See 'probabilistic models', and 'decompositional theories'.)

Defining Features: This term is usually associated with the classical definitional approach, and in that context refers to component properties that are singly necessary and jointly sufficient for category membership. The term is also used to refer to any component properties that are necessary for category membership, thus allowing the notion of necessary components to be included in probabilistic models. The term will be used in the latter, looser sense in this text.
(Also see 'definitional approach', 'characteristic features', and 'well-defined categories'.)

Characteristic Features: This term refers to component properties that, while not necessarily associated with each member of a category, have a reasonable probability of so being, and are accordingly used in making category decisions.
(Also see'probabilistic models' and 'ill-defined categories'.)

Featural Theories: As discussed, this is sometimes equated with decompositional theories. However, it is used here to refer to a subset of probabilistic models which are characterised by the use of features (as opposed to dimensions) as the component properties of each concept. In this sense, it can be thought of as one of two subsets of decompositional probabilistic models.
(See 'probabilistic models', 'features', and 'decompositional theories'.)

Dimensional Theories: This of course refers to the other subset of decompositional probabilistic models.
(See 'probabilistic models', 'decompositional theories',

'dimensions', and 'featural theorie$'.)

Feature-list Theories: This is a term which is sometimes used in a contrast with 'prototype' theories. In this context the class of models referred to is also sometimes called 'feature theories', and one should beware the ready confusion with featural theories and decompositional theories. What is meant is that group of theories which assume that a concept takes the form of a list of component properties. This is compatible with the definitional approach, and also with a subset of probabilistic models termed 'frequency models'.
(See 'definitional approach', 'prototype', 'features', 'decompositional theories', 'featural theories', 'frequency models' and 'prototype-distance models'.)

Well-defined Categories: This refers to those categories of objects for which the concept can be represented as a set of singly necessary and jointly sufficient component properties. While it is usually associated with the definitional approach, many probabilistic models make allowance for their existence.
(Also see 'definitional approach', 'defining features', and 'ill-defined categories'.)

Ill-defined Categories: This term refers to those categories for which there is no simple set of criterial components. The notion is not therefore allowable in the definitional approach, but it is generally assumed in alternative models that most natural concepts are of this nature.

(Also see 'definitional approach', 'probabilistic models', 'characteristic features', and 'well-defined categories'.)

Frequency Models: These models are a subset of featural theories, and are characterized by the assumption that people compile the frequency with which features occur among instances of a concept, and use this information in assigning objects to a category. They are also sometimes called 'feature frequency models'. Frequency models are usually compared with 'prototype-distance' models.
(See 'probabilistic models', 'featural theories', 'feature-list theories', 'characteristic features', 'prototype-distance models' and 'cue validity models'.)

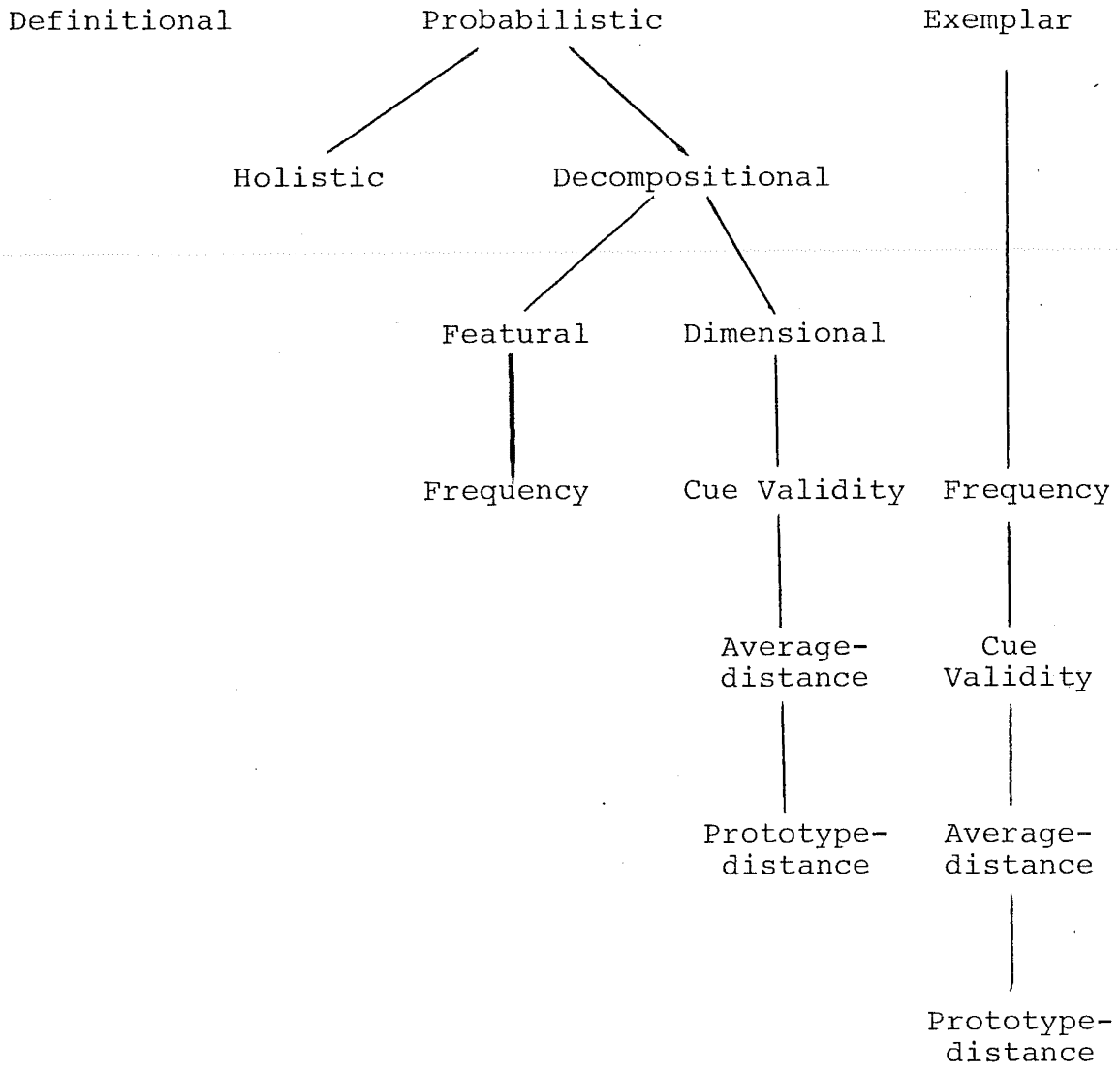
Prototype-distance Models: This refers to a subset of probabilistic dimensional models, in which category decisions are made on the basis of distance from a prototype. This type of model is also sometimes referred to simply as a prototype model.
(See 'probabilistic models', 'dimensional theories', 'feature-list theories', 'frequency models', and 'average-distance models'.)

Average-distance Models: This refers to those models in which category decisions are based on finding the smallest average distance between object-to-be-categorized and stored pattern, where the stored pattern might refer to exemplars or prototypes or some other form of summary representation, and distance reflects similarity. Thus, average-distance models are a subset within the classes of exemplar models

and probabilistic dimensional models.
(Also see 'probabilistic models', 'exemplar models', 'dimensional theories', and 'prototype-distance models'.)

Cue Validity Models: This refers to those probabilistic dimensional theories which include the assumption that people learn the degree to which values on individual dimensions can be used to predict category membership, and that category decisions are based on summing the cue validities of each component property. These models are also sometimes known as 'probability models' (not to be confused with probabilistic models).
(See 'probabilistic models' and 'dimensional theories'.)

Figure 1: Summary Figure Showing Relationships Between Models



Note: the terminology used for the types of theory within the exemplar approach emphasises that the methods used to assess similarity in probabilistic models are extendable to exemplar models, but of course there are important differences in the exemplar models notwithstanding the similar assessment methods.

CHAPTER 4

PERCEPTUAL PROCESSING IN HUMANS

4.1 INTRODUCTION

The essence of 'features' of a concept, is that they are those holistic percepts which define or characterize a concept. In the classical, definitional approach, concepts are assumed to form a hierarchy, such that their description ultimately resides in 'primitive' features, which are isomorphic with single units in the input system. It is the objective of this chapter, to examine the question of whether this assumption is supported by research into lower levels of processing, or whether, as suggested in the previous chapter, features can be configurations of elements, processed integrally, and not necessarily isomorphic with single units.

Information-processing systems in biological organisms may be investigated at three different levels (following Dodwell, 1978):

1. As the detector of signals in a normally "noisy" ambient stimulus environment.
2. As the organizer or integrator of sensory data.
3. As the user of perceptual information for cognitive ends.

The last of these was examined in the previous chapter. In this chapter the first two levels of processing - what may be termed 'signal detection' and 'pattern recognition' are examined.

4.2 THE PROCESSING OF SENSORY STIMULI

4.2.1 Modes of Perceptual Processing

The first level of perceptual processing, 'signal detection', is the processing of stimuli which vary along sensory dimensions. Sensory stimuli, by definition, have properties which are detectable by sensory receptors. While they can be no more than a change on a single dimension (e.g. wavelength), the class subsumes all those stimuli composed of changes on sensory dimensions.

Even at this simple level, analysis appears to be complicated by several factors. For a start, it has been assumed that stimulus generalization is a function of the closeness of stimuli on an objectively measurable, physical dimension. To some extent this is indeed the case, but it is not completely so. For example, people generalize more to tones an octave away rather than to tones physically nearer on the dimension of pitch (Herrnstein, 1982). Part of the reason for this is that pitch perception is not one-dimensional. The interdependence of some physical dimensions in this way clearly strains the simplistic, reductionist approach. Physical dimensions which, when associated in the description of some stimulus, are not separate or independent, are known as integral dimensions. In such a relationship are the dimensions of saturation and brightness. Other dimensions, known as separable dimensions, are independent in effect. Thus, if a stimulus is being described in terms of size and brightness, these dimensions are completely independent of each other.

Following this distinction of integral and separable

dimensions, it has become apparent that there are two modes of perceptual processing: the processing of stimuli in a unitary, holistic manner, and the processing of stimuli by reference to their constituent dimensional components. These are characteristically related to perceptual dimensions such that holistic processing is associated with integral dimensions and analytic processing with separable dimensions.

However, if the mode of processing was totally under the control of the stimulus dimensions, then this concept of processing mode would hardly be a useful one. Growing evidence points to a number of stimulus, processor and task variables being involved in determining mode of processing. For example, it appears that young children (and older retarded children) tend to process holistically stimuli that are analysed by adults, and it has been suggested that individual differences exist among adults. It also seems that processing mode varies according to the nature and conditions of the task (see Foard & Nelson, 1984, for a brief review of this evidence).

It is worthy of note - for future reference - that two of the task factors that are significant are (a) the amount of time and/or resources allowed; and (b) whether the task calls for learning a rule by which to classify, or not. Holistic processing is more likely when time and/or resources is limited, and analytic processing is more likely when rule-learning is required.

The situation is also complicated by evidence that generalization along a physical dimension may be abrupt. Rosch for example, has offered extensive evidence (Rosch, 1977) that colour has 8 to 12 "salient points" which form the

basis of human colour categories. Pigeons too, demonstrate sharp (but slightly different) transitions from one basic colour category to another (Blough, 1961). Again, there are clear, apparently innate, transitions in the perception of speech. For example, people hear a sudden transition between the sounds of /d/ and /t/ at a voice onset time (the time difference between the onset of the plosive burst and the onset of voice) of approximately 35 m/sec.(see Herrnstein, 1982). Curiously enough, similar results have been achieved with chinchillas (Kuhl & Miller, 1975).

4.2.2 Implications

The implications of this information can hardly be appreciated without an understanding of the traditional assumptions of categorisation (discussed in 3.3.1). Very briefly, we can say that categorisation (which may in this context be defined, without processing assumptions, as "the division of the world into classifications by which non-identical stimuli can be treated as equivalent" (Rosch, 1978) was traditionally assumed to be characterized by the following properties:

(i) arbitrariness of category formation;

(ii) equivalence of category members (i.e. each exemplar of a category is equally representative of that category);

(iii) determinacy of category boundaries (i.e. the distinction between one category and any other is clear-cut); and

(iv) decomposability of categories (i.e. membership in a category is on the basis of constituent component properties).

From these four basic properties, two more points may be made. Firstly, the assumption of arbitrariness stems from the

belief in association as the fundamental principle of human behaviour (from British empirical philosophy of the seventeenth century) - that is, a newborn human has a blank mind, and connections between stimuli are formed entirely arbitrarily by association. Secondly, the assumption that categories form a hierarchy, ultimately definable in terms of elemental features, carried with it the implicit assumption that the processing of those features is independent.

The evidence for innate transitions in sensory perception challenges the assumption of arbitrariness. The existence of holistic processing suggests that stimuli made up of more than one stimulus dimension are not necessarily analyzable by breaking them down into component dimensions - if the elements are interdependent, such analysis may lose significant information. Consequently, the analytic processing of integral stimuli is more likely to result in incorrect information. It is clear that the importance of this, as well as the probability and nature of error, will be partly determined by the nature and conditions of the task.

It is not of course assumed that the processing of simple sensory stimuli necessarily tells us anything about the processing of other, more complex stimuli. However, it seems evident that the traditional assumption that patterns and concepts could be broken down into component parts, such that their definition would ultimately reside in those components, was based on an understanding of these simple stimuli - a set of stimuli which seemed to be clearly decomposable into defining values on sensory dimensions.

The extrapolation of those assumptions being made about the processing of simple sensory stimuli to stimuli which were

not definable in terms of the same type of physical dimensions, led to the idea that there were sensory detectors for geometrical features. From this develops the traditional, analytic approach to pattern recognition.

4.3 THEORIES OF PATTERN RECOGNITION

The second level of perceptual processing involves the organization or integration of sensory data - a process considered to be largely automatic. The area of research which deals with this level is commonly entitled 'pattern recognition', and in human studies tends to concern visual pattern, described as "a collection of contours or edges, which in turn are defined as regions of sharp change in the level of a physical property of light (usually intensity) impinging on the retina" (Dodwell, 1970). More generally, 'pattern' tends to be used to refer to a perceptual stimulus which may be seen to be composed of a number of different stimuli. In terms of 'pattern recognition' research, these perceptual stimuli are usually required to have a certain simplicity.

4.3.1 The Analytic Approach

According to this approach, the initial stages of processing are analytic, that is, the pattern is broken down into elementary components (the nature of which varies according to the specific model). Later, a complementary process puts the outputs of the feature analyzers together and creates an internal representation of the pattern. Consideration of the later, synthetic operation has tended to be neglected. In some models for example, the features once

detected are listed, and the feature list compared with feature lists for known patterns. By keeping the pattern as a list of features throughout the processing stages, the pattern is in fact never reconstructed. This approach is typical of computerized pattern recognition.

The analytic approach to biological systems has received a large part of its support from the neurophysiological studies of Hubel & Wiesel (1962, 1965). To very briefly summarise the main points of importance, it appears that in the mammalian visual system (Hubel & Wiesel's work was in fact on cats; the generality of the results is commonly assumed), three main types of neuron can be found. These are called 'simple', 'complex', and 'hypercomplex' cells on the basis of their response characteristics. 'Simple' neuronal units for example, respond to orientation and length of light-dark borders, while complex and hypercomplex cells respond progressively to more general characteristics. These different types of neuron are grouped so that most simple cells are in layer IV of area 17 of the striate cortex, complex cells in the remaining layers of area 17 and area 18, and hypercomplex cells in area 19. They thus can be considered as marking serial steps in the passage of visual information from the retina to the association cortex. In keeping with the classical processing assumption, Hubel & Wiesel suggested that specific patterns of convergence of the outputs of one type of cell lead to the construction of a higher-order type of receptive field - for example, the appropriate convergence of specific simple-cell outputs creates complex receptive fields.

They further suggested that these three neuronal

classes formed the lower levels of an hierarchical system concerned with the abstraction of salient information (such as edges and angles) from visual stimuli. Implicit in this, is the idea that single cells at the top of the hierarchy might represent complete percepts (John & Schwartz, 1978).

Challenges to the Analytic Approach

Although the type of serial processing strategy in which a pattern remains little more than a collection of features throughout the processing stages, is emphasised in most pattern recognition theories, it seems most unlikely that this type of system would be applicable to biological visual systems "which are often able to recognise patterns on a level that transcends the identity of their constituent features" (Hughes, 1982).

The evidence against a purely analytic approach begins with the undeniable evidence that perceptual data are organized and integrated in accordance with a number of principles, which are presumably innate. Many of these principles have been codified and are known as the "Gestalt" principles of organization. Examples are such 'laws' as those of proximity (elements close together in space tend to be grouped together), and similarity (objects that look alike tend to be grouped together). Implicit in these principles is the interdependence of elements in a pattern - the impossibility of decomposing a pattern (and any object may be thought of as a pattern) into a number of independently processed components. Moreover, echoing the evidence that holistic processing is used when time is limited, evidence suggests that humans perceive certain larger configurations

faster and more accurately than their components (see, e.g. Pomerantz, Soyer & Stoeven, 1977).

Further challenges to a pure feature-detector approach, and support for the importance of the configuration of elements come from neurophysiological research. First of all, the idea that there are specialized neurons which divide the visual world into a limited set of perceptual categories by the one-to-one correspondence of category and specialized "feature extractor", requires that the responsivity of a single cell be uniquely specifiable. But the evidence is clear, that multivariate stimulus features contribute to the firing rate of a single cortical cell (John & Schwartz, 1978).

There is a growing body of evidence which suggests that in fact spatiotemporal patterns of neural activity are the basis for information processing. Some of this evidence is very briefly noted here (from John & Schwartz, 1978):

(i) evidence that information and function are distributed across extensive anatomical domains and that the brain is capable of reorganising information processing following injury to areas of the brain (see, e.g. Dru, Walker & Walker, 1975 re rats; Sprague, 1966 re cats; Griffith & Davidson, 1966 re humans);

(ii) evidence that most neurons in the brain are continuously active and each may be shown (if observed long enough) to significantly alter its firing pattern consequent upon the presentation of any stimulus (Burns & Smith, 1962, cats);

(iii) evidence that the relationship between neuron firing patterns and event-related potentials (waveshapes which reflect the processing of stimuli, in particular,

components of ERPs appear to reflect parameters of the physical stimulus) is not invariant; that is, neurons which demonstrated one relationship to the waveshape could be observed to change to another relationship sometime later (Ramos, Schwartz & John, 1976, using cats); and

(iv) evidence that the activation of some neurons in different regions of the cortex is triggered when subjective images of whole objects are retrieved from memory, that is, by the image of a concrete goal (see Shvyrkov, 1981).

In summary, it appears that some neurophysiological evidence supports the view that processing of even simple well-defined stimuli, is a function of neural circuits rather than single neurons. It is interesting to note in this context, that recent physiological evidence supports a view of memory as dependent on changes in connectivity between elements of interconnected groups. In particular, there is clear evidence that precisely specified changes in synaptic connectivity store memory in invertebrates (see Faley & Alkon, 1985, for a review of this evidence). To quote Kruglikov (1978): "The material substrate of memory is a system of elements; the functional role and real contribution of each element to the function of memory are realized only when this element is incorporated into a system, hence are never independent of such a system". This is congruent with the growing evidence that spatiotemporal and configurational characteristics of neuronal activity are more important in the processing of data than the activity of single neurons.

There is also more specific neurophysiological evidence

against the pure analytic approach, as expressed in the transcortical model of Hubel & Wiesel. The most direct comes from a number of behavioural demonstrations of substantial capacities for complex spatial vision in destriate animals (see for example, Humphrey, 1974; Keating, 1975; Hughes, 1977; Sprague et al, 1977; Dineen & Keating, 1979). Moreover, while there is no doubt that damage to area 17 has severe consequences for visual perception, removal of areas 17 and 18 has virtually no effect on learned discriminations of simple patterns or forms in the cat (Sprague et al. 1977; Bertucchi & Sprague, 1980). On the other hand, cats with large extrastriate lesions have impaired pattern and form discrimination (ibid). Recent studies by Sprague & Hughes (Hughes, 1982) provide evidence for the importance of global structural cues in pattern perception. It appears that local feature analysis occurs in the striate cortex, but global configurational processing occurs in the extrastriate cortex. Which strategy is employed may well depend on certain aspects of the input pattern. This suggestion implies that the perception of stimulus configuration precedes detailed feature analysis. In contrast, most serial-processing approaches assume that configurational analysis depends on feature analysis.

The idea that configurational perception precedes feature analysis, is also supported by the evidence that the nature of a visual scene determines to a large extent the scan path used to study it (Neisser, 1967). It is clear that this requires a mechanism that doesn't rely on focal attention, but can analyze the visual field in sufficient detail to extract enough information to decide what in the

visual field should be focussed on. Neisser called this process 'preattentive vision', and it seems clear that such a process precedes the formation of a figure-ground perception, and is based on gestalt factors of perceptual organization (Hughes, 1982).

It is worth noting therefore, that work in the field of artificial intelligence suggests that gestalt-type grouping actually results in the formation of a figure-ground distinction (Marr, 1976). Moreover, it seems that feature analysis is often inadequate to distinguish form boundaries unless a gestalt-like grouping process has been carried out (ibid). It seems that the grouping process reduces the amount of information by organizing the data base in ways that aid in subsequent object recognition.

It is clear that the analytic approach fails to take into consideration this relational aspect of pattern recognition. Of those who have examined the way in which integration occurs, the most prominent approaches have been the motor integration theories, figural synthesis models, and field theories (Dodwell, 1982).

4.3.2 Motor Integration Theories

Motor integration theories (as propounded most prominently by Hebb, 1949; and Hochberg, 1968), propose that 'integrated wholes' are constructed from certain primitive elements by the sequencing of eye movements and neuronal structures which are organized thereby. For example, Hebb hypothesised that neurons were interconnected in sets, such that the firing of one neuron affected the probability of the firing of others in the set. Spatio-temporal contiguity of

firing within the set (determined by built-in eye movement processes) changes these probabilities, leading to the development of an organized perceptual field. Thus the integration of visual data is a function of the repetitive sequential fixations of visual receptors, which sequence is partly influenced by experience.

Probably the major weakness of this type of theory is its failure to adequately explain (a) how different classes of input give rise to identifiably different outputs, and members of particular classes of input give rise to the same output; and (b) how input classes are initially generated (i.e. the first stages of perceptual learning).

4.3.3 Figural Synthesis Models

Of major importance in the popularity of a feature-detector approach, was the research done by Hubel & Wiesel (1962; 1968), pin-pointing cortical detectors for orientation in cats. Although this approach has had some success, its promise has not been fulfilled. One reason for that is the neurophysiological evidence that spatial frequency, orientation and movement are the primary parameters of coding, rather than the line segment system advocated by Hubel & Wiesel (see Campbell 1974 and Robson, 1975 for a review of this evidence). Consequently, spatial frequency models (subsumed under models of figural synthesis) rose in popularity.

These models postulate a frequency-analysis mechanism of some sort. One hypothesis, for example, is that a Fourier analysis is performed by the visual nervous system on the coded inputs (individual cells coded for spatial frequency

in a specific orientation), and the frequency components are then synthesised into a new and abstract representation of the input pattern (Campbell & Robson, 1968).

However, it seems unlikely that such a model, involving any type of frequency analysis, could operate at any sophisticated or global level (see Sekular, 1974; Robson, 1975; Glezer et al. 1973).

4.3.4 Field Theories

(a) Geometrical Models of Vision

Gestalt theory is of course the most prominent of the field theories, but the success of this approach has proved to be limited to the formulation of a set of organizational principles. For a deeper analysis, beyond the level of mere description, geometrical concepts have proved to be useful tools, and a number of geometrical models of vision have been proposed. Examples include:

(1) Luneburg's (1947) Theory of Binocular Visual Space

Without getting into the geometrical details of this model, and at the risk of over-simplifying, one can say that the essentials of Luneburg's theory are that there is a consistent one-to-one mapping of the points in a visual field onto points on the retina ('binocular space') which is defined by two basic measures:

(i) convergence of the eyes; and

(ii) their elevation from the horizontal plane of regard.

Although the points in the visual field are points in a three-dimensional physical space that is Euclidean, it follows from the requirements of Luneburg's model that the

binocular visual space be non-Euclidean and in fact hyperbolic. Thus the 'rules' which are true in physical space are not, by and large, true in binocular space (e.g. in Euclidean space two distances that are equal to a third distance are necessarily equal to each other, but this is not true in hyperbolic space), and consequently distances between points in binocular space cannot be measured in the same way we measure distance in physical space.

Experiments undertaken to test this model (see, e.g. Zajaczkowska, 1956; and Blank, 1958) have clearly demonstrated that the space of binocular judgements is not a simple Euclidean space. This evidence however, is restricted to highly artificial situations, and the validity of the model outside a static situation is doubtful. Nevertheless, this in itself is important, for its implication that the normal space of visual judgements appears Euclidean partly because of cognitive judgement regarding the nature of physical objects and events. That is, the limited validity of this model clearly demonstrates the influence of higher level processing on lower level processing.

(2) Watson's (1978) Variable Space Theory

There are a number of visual illusions that demonstrate a lack of congruence between what is seen and what is known about the physical measurements of the object. While numerous theories to account for these phenomena have been proposed, none have succeeded in accounting for more than one illusion and its variants. Typical of these theories is the assumption that visual space has a fixed geometry, and that the illusions are aberrations. Watson (1978) has hypothesised that the

geometry of visual space is variable, and depends in a precise way on the configuration of elements in different parts of the visual field, which interact as functions primarily of local contrast and separation between elements. Thus, illusions are seen to be, not aberrations, but natural consequences of the processing mechanism.

As with the Luneburg theory, the applications of this model are limited. Again, it has only been worked out for static configurations, and again, the geometry is probably usually overridden by other aspects of visual processing. However, its success in accounting for diverse phenomena of visual illusions supports the basic thesis of geometrical models.

(3) Lie Transformation Group Theory

Hoffman (1966, 1971, 1977) has attempted to answer the question of "(how) the local, microscopic processes in the visual field generate macroscopic events that yield the perception of contours, objects, and visual space generally" (Dodwell, 1982), by applying the mathematics of continuous transformation groups (worked out by Sophus Lie in the nineteenth century) to visual processing.

The mathematics is somewhat complex, but the essence of this theory can be articulated fairly briefly, if over-simplistically.

A transformation is an operation that maps a geometrical object onto some other object. Such operations can be represented by vectors, which have both origin and direction. A vector expresses a purely local property, but a field of vectors, by the way in which the vectors can be combined, can

express macroscopic or global properties. A field of vectors can be thought of as potentially generating all the paths across the manifold (i.e. a smooth surface on which continuous transformations can occur; here identified with both the visual field and its cortical representation), and it may well be that the structure of the manifold determines which paths are most easily generated upon it.

Hoffman observed that many visual phenomena occur in such a way that pairs of processes are orthogonal to each other, for example, the orthogonal or (Lie orbit) pair for horizontal and vertical translations, and the pair for dilation and rotation (consisting of a star of radial lines and a set of concentric circles). The generator of a translation is called a Lie operator, and Lie operators will, under a specific set of simple restrictions, form a closed system called a Lie algebra. Thus, under these restrictions, the Lie operators possibly are limited both in number and complexity.

The general posulate of the theory is that the visual system seeks out those Lie operators which will reduce the output for any path to zero. The simpler the operators, the easier discriminations involving them will be.

This of course, points to an easy test of the theory, in that it makes explicit predictions concerning what sort of discriminations will be easy. Although there have been few explicit tests of the theory as yet, some fairly strong empirical support has been received (see, e.g. Caelli, 1974, 1977; Wilkinson & Dodwell, 1980).

One in particular is the experimental study undertaken by Wilkinson & Dodwell. In this, the prediction of the theory, that radial line/concentric circle discriminations will

be easy, was tested using young kittens. Surprisingly, but in accordance with the theory, it was found that the discrimination was even easier than the traditionally simple discrimination of horizontal vs vertical translations (note: this result is the opposite to what would be predicted by a simple feature-detector model, or spatial-frequency theory). Moreover, sets of rectangular hyperbolas at 45^{o} angles from each other, are also relatively easy for young kittens to discriminate - this pattern is the third fundamental Lie orbit pair.

(b) Implications

The present degree of understanding is not such that we should choose one model and discard the others. Indeed, Dodwell (1978, 1982) suggests that the complexity of the visual system is such that it is unlikely that any single model will be adequate to explain it. It should not be assumed then, that any of the models put forward here are necessarily incompatible with any others. Nor should the limited power of some models to explain a wide variety of visual phenomena, be taken as justification for disregarding their possible contribution to our understanding of visual processes. Luneburg's model, for example, makes a major contribution in its conceptualisation of the conditions under which mapping from the physical world to the visual system can be achieved. The success of Watson's application of Riemannian geometry in explaining visual illusions gives credence to the basic concept of geometrical models.

The success of these models (especially the most general of them - Lie Transformation Group theory) in explaining diverse phenomena of pattern recognition, suggests that

the approach may well be the most nearly accurate one yet postulated. In particular, the fundamental principle of 'mental space' having a geometry and structure of its own, which governs the representation of objects, appears to be strongly supported.

In summary, we may say that

(i) a pure feature-detector approach makes no allowance for the importance of relational aspects of stimuli;

(ii) the importance of relational aspects is suggested by the so-called Gestalt principles; and

(iii) neurophysiological evidence provides extensive support for the idea that spatiotemporal patterns of neural activity are the basis for information processing, and for the existence of a mode of visual processing which is concerned with global configurations.

The success of geometrical field theories indicates:

(iv) a lack of congruence between objects in physical space and images in visual space; and

(v) that visual space has a geometry and structure of its own, which governs the representation of objects.

Moreover, the nature of this geometry allows a distinction between 'pattern' and 'feature' (easily perceived as arbitrary in many situations) to be made - that is, if 'feature' is defined as the constituent components of a decomposable stimulus/pattern, then these approaches can be seen to allow a redefinition of feature as a unitary, holistic percept (i.e. not further decomposable) - thus making the point that a feature may be a configuration of elements, which is not decomposable because the configuration is as important as the component elements.

4.4 SUMMARY

This chapter has been concerned with the first two levels of perceptual processing. Research at the first level - that of the detection of sensory stimuli - has uncovered evidence that challenges a view of stimuli as being generally decomposable into component dimensions which may be independently processed. Instead, it seems likely that such analytic processing may, in certain circumstances, result in the loss of significant information, and that the importance of this loss is partly determined by the nature and conditions of the task being carried out by the processor (i.e. by the processor's goals).

Pattern recognition research is supposedly concerned with the organisation and integration of these elemental stimuli. However, the distinction between 'patterns' and many of the 'elemental' stimuli often may seem somewhat arbitrary. Thus, for example, stimuli which are presumably simple patterns, such as line segments, are grouped with the more directly sensory stimuli, and assumed to be likewise perceived by unit detectors (though of the cortex rather than by peripheral sensory receptors).

One perspective which resolves the arbitrary nature of the distinction, is the view that theories of pattern recognition are implicitly theories of the nature of the 'feature' (i.e. element). Thus the evidence for Gestalt laws, with their message that some patterns convey more information than can be conveyed by the independent processing of their constituent parts; the successes of theories which postulate internal representations of a more holographic nature; and

the neurophysiological evidence for processing being a function of neural circuits rather than single neurons, and memory a function of changes in synaptic connectivity; are all interpretable as justification for a definition of 'feature' as a unitary, holistic percept - i.e. a stimulus which cannot be further decomposed, without loss of significant information, within the processing system. The important distinction of this definition from the standard definition of feature in categorization research, lies in those words "without loss of significant information".

CHAPTER 5

DISCRIMINATION IN NON-HUMAN ANIMALS

5.1 INTRODUCTION

The classical empiricist tradition assumed that sensory features provided the primitive elements which defined a category, and members of categories were identified on the basis of this set of defining features and rules defining their relationship. This was assumed to be a general principle, applicable to such diverse classes of object as that of simple geometric forms (such as a square), and that of superordinate lexical categories (such as fruit). These, it was considered, varied only in complexity. This of course, made it possible to significantly simplify experimental research into categorization by restricting the test stimuli to well-defined objects, such as simple perceptual forms.

Despite this view, which sees human concepts as composed of defining features and rules, it has been common to assume that the evidence that animals recognize objects on the basis of a few criterial properties, means that they are 'discriminating' rather than 'conceptualising' or 'abstracting' (as humans are said to do). What is the assumed or perceived difference between human and non-human object classification that leads to this difference in terminology?

What does it mean to 'abstract'? The term refers to a process of taking something out; the implication is that humans categorise objects by picking out specific features or

attributes. To 'discriminate' on the other hand, simply means to act on the basis of there being a difference between two or more objects. It is clear that the word involves no assumptions about what is involved at a cognitive level. To 'abstract' on the other hand, suggests an active process.

It seems fair to suggest that the distinction was by no means clear to early theorists in the field. Initially, research focussed on the passive and gradual learning of the defining features. It was not until the mid-1950s, that the emphasis shifted to the subjects' active hypothesis testing in the learning of relevant features and the logical rules combining them (Mervis & Rosch, 1981).

The possibly active nature of the selection process in non-human animals has been far less considered. Nevertheless, the entire structure of the early behavioural experiments in the laboratory assumed that animals could learn what information was significant in particular situations. And indeed, in Sutherland's (1968) theory of pattern recognition, we see acknowledgement of the possibility that some non-human species form rules for the combination of features, and that such a process is "akin to induction" (Sutherland, 1969).

The other traditional approach to stimulus classification was that of the ethologists, who found an analogously simple set of stimuli in the natural environment, namely, the so-called 'releasing stimuli' which provide the initial triggers for fixed action patterns. These are stereotyped, species-typical behaviours, which are apparently innate, and require no learning. The applicability of the results of this work to questions of the flexibility of stimulus classification in non-humans, is doubtful.

The concern of this chapter is precisely that - the flexibility of stimulus classification in non-human species. It is the contention of the writer that, for reasons relating to the way in which these cognitive processes evolved, both the 'definitional' and the 'probabilistic' cognitive processes will be utilized by some animals (including humans). In others, only the 'definitional' process will be used; while in still others, the processing of information is of a passive nature which doesn't warrant the title 'cognitive process', but may be regarded as pre-definitional.

To provide support for this thesis, we will look at neurophysiological and behavioural evidence for the existence of two different modes of perceptual processing (level 2), which imply two different types of feature. We will then look at a few examples of diverse behaviours within two functional classes of natural behaviour - prey recognition and call recognition - and demonstrate the range of information processing systems involved. Namely, from a passive feature-extractor process to two distinct cognitive processes, which may be interpretable as 'definitional' and 'probabilistic'. The results of the artificial test situations used to investigate discrimination in the laboratory will then be discussed, for the evidence that they provide that different cognitive processes are demonstrated in different situations.

5.2 MODES OF PERCEPTUAL PROCESSING

In Chapter 3 we concluded that it was the changing nature of the feature which underlies a discontinuity in the evolution of intelligent behaviour. The nature of the feature

in human processing systems has been suggested as being an holistic percept, which may be configurational, not isomorphic with single units in the processing system, and integrally processed. This view of the feature is in direct opposition to the idea of the feature which is implicit in the traditional view of the information-processing system - namely, that processing is serial and begins with the analysis of features which are independently processed and isomorphic with single neuronal units. At the second level, the level at which the nature of the feature is most clearly displayed, these opposing views may be thought of as the "Gestalt perception process" and the "stimulus summation process" respectively.

The hypothesised change in the nature of the feature from that implicit in the Gestalt perception process, is supported by neuroethological evidence. Before looking at the processing systems evidenced by diverse examples of perceptual coding mechanisms, it should be noted that it is not the author's contention that a Gestalt process replaced a summation process. Rather, it is considered that the evolution of a summation process preceded that of a Gestalt process, and that it was the evolution of a Gestalt process (co-existing with a summation process) that gave rise to the 'probabilistic' cognitive process.

A few examples of perceptual discrimination exhibited by different non-human species (from Hailman, 1970) provide support for this thesis.

The first is that of the frog's colour discrimination. The escape response of frogs when frightened is to leap into the water. This response appears to be partly directed by the water's blue colour, and is evidently a true colour

discrimination rather than merely a spectral sensitivity. Muntz (1962) has demonstrated that the discrimination of 'blue' is stable over a great range of intensities and spectral bandwidth. That the discrimination is not due to a single type of receptor is indicated by the evidence that green light inhibits the response to blue. This response to blue light is however, only evident in adults. Tadpoles respond to green light - a response which appears to be mediated by a single visual pigment contained in the cones (Muntz, 1963). This difference in response is probably a function of the early development of cones in the retina, and the later development of rods.

It appears that here we have an example of a perceptual discrimination which:

(i) is coded within the eye by third-order neurons;

(ii) develops because of maturation of the sensory apparatus; and

(iii) results from a passive process involving the combination of separable, primitive features (i.e. those isomorphic with single neuronal units).

A similar example can be found in the preferences of laughing gull chicks for red and blue wavelengths over green and yellow wavelengths. This preference relates to their pecking response to the red beak of their parents. As in the frog, the discrimination appears to be largely independent of wavelength purity (Hailman, 1964; 1967), and the inhibitory effect of the middle wavelengths suggests that at least two receptor types are involved. It appears that, in the laughing gull chick's colour preference, we have another example of a perceptual discrimination coded within the eye, probably by

second-order neurons, and interpretable as resulting from a passive process involving the combination of separable, primitive features. In contrast however, this discrimination is evident at birth.

On the other hand, the pecking response of a laughing gull chick is mediated by more than a colour preference. Also involved are a number of characteristics which relate to a form-movement discrimination: oblong shape, about 9 mm in width, vertically oriented, moving horizontally at a specific speed, being darker than its background, and being visible at eye level by both eyes. Most of these parameters could be coded by the type of neuronal unit commonly referred to as 'feature detectors'. However, during ontogeny, the gull chick's response alters, such that effective models must more closely resemble the parent's head (Hailman, 1962; 1967). The evidence suggests the development of a "qualitatively more precise Gestalt" (Hailman, 1970). The change appears to be a result of specific experience with an environmental object (usually the parent), because chicks can be taught to prefer a model of another species (Hailman, 1967) and to respond preferentially to an originally non-preferred stimulus (Schmerler & Hailman, 1965).

It seems then, that in the laughing gull chick's form-movement discrimination we can see a change in the mode of perceptual processing from a stimulus summation process to a Gestalt perception process. The use of the latter strategy, in this case at least, appears to require experience with stimulus objects.

Hailman (1970) makes some generalizations based on these and other examples: that coding may take place in

serial steps as neural information is sent to the brain; that it appears that the further the units are from the initial receptors, the more complex they become (as regards the nature of the external stimuli effective in exciting them); and that a given degree of complexity may be found in different loci in the sensory systems of different animal species. From this, he defines the coding mechanism for releasing stimuli as "the entire sensory system up to and including the level at which single units respond to a stimulus that is isomorphic with the releasing stimulus for behaviour of the whole animal" (Hailman, 1970).

However, he notes Erickson's (1963) argument, from studies of the coding of learnable sensory discriminations, that there are no single units responsive to stimuli isomorphic with releasing stimuli - that the relevant neural information is contained in the amount of neural responses across many units. Hailman suggests that the coding for stereotyped, species-typical perceptual preferences (as evidenced in the so-called 'fixed action patterns') might be organized differently from the coding that underlies learnable discriminations.

It is possible that in the laughing gull chick's form-movement discrimination, we see a change from a stereotyped, species-typical perceptual preference to a learnable sensory discrimination - thus a change from a process using single units responsive to stimuli isomorphic with releasing stimuli to one in which the relevant information is contained in patterns of neural activity.

The development of a stimulus summation process to a Gestalt perception process during the course of ontogeny is

also seen in behavioural experiments with human babies, such as the evidence that over the first six months of life, faces come to be recognized less by their single components and more by the "integrated" configuration (Bower, 1966).

To quote Hebb (1949): "Animal experiments and the human clinical data alike indicate that the perception of simple diagrams as distinctive wholes is not immediately given but slowly acquired through learning".

The point is made by Ewert (1980) that "unambiguous classification of a configurational stimulus to a category of meaning is largely independent of variations of certain other parameters...The construction of invariants appears to be a precondition for Gestalt perception." The construction of invariants (note that if invariants simply resulted from the absence of appropriate detectors then 'construction' would be inappropriate terminology) points to the fact that some information comes to be regarded as significant and some is not. In so far as the active selection of significant information (i.e. a selection process which is not merely a function of what the organism can detect) is not part of the type of passive, hierarchical system postulated by Hubel & Wiesel, the construction of invariants challenge this type of process (note: the construction of invariants has not been revealed by single-unit recording methods (Ewert, 1980)). Moreover, it suggests the requirement of the active selection of significant information before a Gestalt perception process can develop. This is compatible with the evidence that learning, or at least experience with appropriate stimuli, is required before the stimuli can be processed as an integrated whole.

It seems reasonable to suggest then, that Gestalt processing is always preceded by stimulus summation processing, ontogenetically speaking, and thus always co-exists with it. This is what is predicted by the thesis that stimulus summation processing evolutionarily preceded Gestalt processing, and that the two modes of processing co-exist in any organism capable of Gestalt processing.

However, Gestalt perception processing is a mode of processing which occurs at the second level of information processing systems (see 4.1), and it is the cognitive processes (third level) which are said to represent a qualitative difference in the evolution of intelligent behaviour. The relationship between the processes at the two levels is seen as being that the development of Gestalt processing of perceptual stimuli necessitated a change from a "definitional" cognitive process (that is, one based on the independent processing of primitive features and their integration by simple summation-type rules) to a "probabilistic" cognitive process (that is, one based on the assessed similarity of patterns).

From this, we can make two testable predictions:

(i) that animals who demonstrate a capacity for Gestalt processing will also demonstrate the use of a "probabilistic" cognitive process in appropriate circumstances; and

(iii) that animals who only have a capacity for stimulus summation processing will only use a "definitional" cognitive process.

The nature of the cognitive processes evidenced by diverse species is the subject of the next section.

5.3 COGNITIVE PROCESSES IN NON-HUMAN SPECIES

5.3.1 Prey Recognition in Frogs and Toads

The main impetus for a feature-detector approach to object recognition in non-human species, (aside from intellectual conviction), comes from a series of experimental studies on frogs (Barlow, 1953; Lettvin, Maturana, McCulloch & Pitts, 1959). To very briefly summarize their findings, it appears that a frog's eye is equipped to extract four patterns of information:

(i) edge detectors, that respond to the border between light and dark areas;

(ii) moving contrast detectors, that respond when an edge moves;

(iii) dimming detectors, that respond when overall illumination is lowered; and

(iv) convex edge detectors, that respond to small, dark, roughly circular, moving objects.

These detectors are sufficient to enable the frog to be warned of possible danger (by the presence of moving shadows) and to catch flying insects.

However, as Grüsser & Grüsser-Cornehls (1968) have shown, every effective stimulus that evokes a particular kind of response also triggers several classes of neuron. It appears therefore, that perception of prey is not coded by a single class of neurons, but by the relative patterns of activities in the four classes (Hailman, 1970). That the integration of this information is a result of a simple summation process of the sort that is characteristic of a 'definitional' cognitive process is supported by the recent experimental work under-

taken by Ewert into prey recognition in toads.

One of the major features of importance for toads in identifying prey, is the direction of movement relative to the object's long axis. The discrimination between a stripe moving in the direction of its long axis and one moving perpendicular to it (what Ewert calls the "worm-antiworm" discrimination), appears to be innate, demonstrable immediately on the toad's metamorphis to the terrestrial environment.

The main points of interest regarding prey recognition in toads are summarized below (from Ewert, 1982):

(i) the worm-antiworm discrimination is unaffected by alterations in plane orientation;

(ii) however, within the vertical plane, toads are more responsive to upward movements than downward;

(iii) this effect is particularly evident when the shape of the stimulus is less like that of natural prey;

(iv) stimuli on homogenous backgrounds are not detected when the luminance of stimulus and background is the same, but equal luminosity doesn't affect detectability when the background is structured (i.e. patterned);

(v) the worm-antiworm discrimination is not disturbed by a structured background;

(vi) discrimination of small (black) 'worms' of different lengths is better on a structured background, but white 'worms' are apparently masked by it;

(vii) stationary stimuli, and ones moved with (rather than against) the background, are also apparently masked by a structured background; and

(viii) there are (at least) four main types of feature which come to govern prey selection with experience: area components, tips leading the stimulus in the direction of movement, isolated dots, and striped patterns (all components of natural prey).

The ability of toads to classify stimuli on the basis of experience has been demonstrated in several studies (Schneider, 1954; Ewert, 1968; Brzoska & Schneider, 1978).

Neurophysiological studies have found a number of different neurons involved in the discrimination process. Retinal ganglion cells are sensitive to stimulus area and, as regards configuration, principally sensitive to lengthening of the stimulus perpendicular to the direction of movement. One of the classes of neurons in the caudal dorsal thalamus and pretectal region is sensitive to the entire area of a moving stimulus, and to elongation perpendicular to the direction of movement. A type of neuron in the optic tectum is sensitive to the entire area of a moving stimulus, and to expansion in a horizontal direction of movement. Other neurons in the same region are stimulated by perpendicular elongation, and inhibited by horizontal expansion. No neurons have been found which respond selectively to a stimulus of one particular configuration.

These classes of neurons which have been identified by Ewert have been given by him the general name of "Gestalt decoders". We may say that these Gestalt decoders usually have ellipsoidal, radially symmetrical receptive fields, which evaluate the orientation of a stripe pattern relative to its movement direction. In contrast, the classical "orientation detectors" of Hubel & Wiesel have longitudinal

receptive fields which evaluate the orientation of a stripe pattern in relation to the orientation of the main axis. Orientation detectors (so-called "simple cells") can extract the background structure from a stimulus even when both are moving together - an ability which Gestalt decoders lack. However, if the background is structured (surely a more natural situation), Gestalt decoders maintain their selectivity, while orientation detectors do not. In some respects then, it appears that the toad's Gestalt decoders share some of the functional properties of complex and hypercomplex cells in the mammalian visual system (Ewert, 1980).

However, as Ewert points out, the evidence that toads can distinguish detailed structures within a functional classification (such as prey) cannot be readily explained on the basis of simple Gestalt classification. Ewert and von Seelen (1974) have put forward a general model of neuronal processing within which Ewert (1982) suggests that the processes of prey recognition evidenced by the toad, are explicable. In brief, this model describes a processing system in which the neuronal units associated with the configurational and featural cues governing prey recognition are integrated by a relatively simple summation-type process, described by Ewert as involving filter operations in the space and time domain and a weighted two-dimensional subtraction of stimulus distributions.

Very generally then, it seems fair to suggest that in the toad, we have an example of configurational stimuli being isomorphic with single units in the input system, and 'cognitive' processing by summation-type integration of configurational units (i.e. definitional).

5.3.2 Prey Recognition in Jumping Spiders

Although comparatively simple creatures in many respects, salticids possess a visual system that rivals that of many mammals in its sophistication. The main points of interest regarding salticids' recognition of prey are:

(1) the hunting behaviour pattern is made up of a number of separable units, each of which is released by different stimuli;

(2) the stimulus characteristics of principal importance are size, speed of movement and solidity, and it is the interaction of these properties that chiefly determines which behavioural unit is triggered (Drees, 1952; Land, 1969);

(3) in some situations, geometrical features also appear to be relevant - again, in interaction with the other factors (Forster, 1979a); and

(4) the features of significance appear to be such characteristics as roundness and symmetry (Forster, 1979b).

Thus, for example, stationary stimuli of whatever nature are totally ignored if 5 cm or more away; two-dimensional stationary stimuli are still ignored at less than 5 cm distant; if solid, 5 mm models are responded to less often than 2 mm models; while a dead fly is responded to more frequently still. Again, two-dimensional stimuli induce hunting responses when moved at a rate of about 1 cm/second, releasing orientation and running at a distance of 10 cm; at a speed of about 0.5 cm/second, the same behaviour is released, but the critical distance and the intensity of the response is smaller; at a speed of about 0.25 cm/second, stimuli are

effective only at a maximum distance of about 4 cm.

As with the frogs, it appears that recognition of prey is based on the interaction of several receptor systems (Forster, 1979a; 1979b). However, the evidence supports the view that this is a passive process; there is no evidence that salticids can learn to modify their classification of prey objects (Drees, 1952), nor that their recognition of prey is other than innate.

In jumping spiders then, it would appear that a passive process involving the combination of features isomorphic with single units in the input system (like those demonstrated in the simple perceptual discriminations detailed in 5.2) underlies prey recognition.

5.3.3 Prey Recognition in Cuttlefish

A far more sophisticated system is observable in cuttlefish (Sepia), and was investigated by Wells (1962). Here, recognition of mysids (a type of shrimp) appears to be innate. However, after five to ten experiences with mysids, young Sepia begin to generalize. This generalization appears to be based on physical similarity to the 'prototypical' mysid, and some of the features that are significant are: movement along the long axis, rather than up and down; size; elongate shape; contrast with background. The precise nature of the perceived similarity could not, however, be determined - although it is interesting to note that the model that was most effective was also the one that looked most like a mysid to the experimenters.

The extent of the generalisation varied considerably among the young cuttlefish, but sometime after the first month

of life, they begin to develop more selectivity. This selectivity appears to result from the experiences the individual Sepia have with various prey. Their failure to learn earlier is correlated with the late development of the vertical lobe - a neural structure known to be involved in learning and memory.

Sepia then, appear to demonstrate a process of prey recognition based on:

(a) innate recognition of one type of natural prey;

(b) generalization through physical similarity; and

(c) appropriate modification of generalization through learning.

It appears clear that prey recognition in the adult cuttlefish involves an active (i.e. inductive) selection process. Moreover, the process of recognition appears to be based on similarity judgements rather than on sets of defining features and rules for their combination - that is, on a 'probabilistic' cognitive process.

5.3.4 Comparison of Processes of Prey Recognition in Different Animal Species

Research on frogs suggests that they have detectors which are responsive to a particular type of configuration - namely "small, dark, circular, moving" objects. However, it seems that the responsivity of the single units is not uniquely specifiable - that is, single units respond to multivariate stimulus features. It is likely that prey recognition is based on a simple summation-type process which integrates features isomorphic with single units. While we lack the data to state this with any surety, the classification of

prey in frogs does not appear to be a flexible one - that is, it is probably innate and not modifiable by individual experience. The process of prey recognition in frogs thus is probably an essentially passive one - wholly compatible with the traditional assumption that non-human species identify stimuli according to specific criterial features to which particular neurons or receptors are sensitive, and a genetic predisposition to perceive the environment in a particular way.

Recent research on prey recognition in toads suggests a process whereby an innate discrimination of a particular type of configuration (which is detectable by a single type of neuron), moving in a specific fashion and interacting with 'rules' regarding how the environment is perceived, is modifiable by experience. From the toads' experience with prey, other more subtle features can come to govern prey selection. It is clear that the process of prey recognition is not a peripheral mechanism, but rather a function of a central processing system. Moreover, the role of experience suggests that it is an active process, whereby the toads 'select' the aspects of stimuli which are useful in identifying their category.

Prey recognition in jumping spiders is a clearer example of the type of process hypothesised as occurring in frogs. The clear innate quality, and unmodifiability of the prey classification, is evidence of the passive nature of the process. Recognition appears to be a function of a simple summation process acting on features isomorphic with single units.

Cuttlefish on the other hand, demonstrate beautifully

the development of a process of prey recognition. Recognition is initially innate, and specific to a particular configuration; but it then generalizes according to physical similarity, later becoming more selective as the cuttlefish gains experience with prey objects. Prey recognition in the adult cuttlefish is a clear example of an active selection process underlying a 'probabilistic' cognitive process.

5.3.5 Bat-Call Recognition in Moths

A behaviour which is highly adaptive and appropriately variable, but without doubt 'instinctive', is the recognition of bat calls by many nocturnal moths. Because bats prey on moths, an ability to avoid bats is clearly of considerable value to moths. Many species have evolved auditory organs which are capable of detecting bat chirps at a distance far greater than the sensory range of a bat. Depending on how close the bat is, the moth will respond to its presence by either turning away or diving to the ground (Roeder, 1966).

This strategically sound behaviour is based on a system of beautiful simplicity. The moth has aural detectors which are triggered only by sounds in the 17-100 kHz band (ultrasound). It has no way of discriminating between sounds in this range, except by loudness. The presence of two sound-sensitive cells, each with different thresholds, allows, by their differential responsivity, a distinction to be made between 'near' and 'far'.

This is clearly an example of perceptual discrimination which is passive, and determined simply by the existence of appropriate detectors.

5.3.6 Frog Recognition of Mating Calls

On the other hand, the ability of frogs to recognise and respond selectively to a number of different frog calls, is much less explicable in these simple terms.

One series of experiments that has been done in this area (Capranica, 1965; Frishkopf, Capranica & Goldstein, 1968) has investigated the ability of male northern bullfrogs to distinguish the mating calls of conspecifics from those of 33 other anuran species. It appears that the basis of this discrimination - which is readily made - is found in the following spectral characteristics of this species' mating call:

(i) pulse repetition rate of 100 Hz;

(ii) energy in the low region (centred at 200 Hz);

(iii) energy in the high region (centred at 1400 Hz); and

(iv) less energy in the medium region (centred at 500 Hz) than in the low region. (from Brown, 1975)

The interesting point to note is that, although there exist 2 types of neuron in the bullfrog's auditory nerve, of which one is most sensitive in the low frequency band and the other in the high, recognition is plainly not simply a function of exciting neurons. Not all sounds which excite the neurons evoke the appropriate response - only sounds with a certain relationship among low, medium and high frequencies. This it seems is because sounds in the medium range inhibit neurons with a low threshold. However, if responses were solely determined by the peripheral mechanism, loud sounds would be effective even without the correct spectral characteristics. As they are not, it is clear that some central, top-down processing is involved. The discrimination

made by the bullfrog is, after all, subtler than that of simply recognising conspecifics. Sounds evoke a number of diverse behaviours, including calls of various kinds, and responses such as escape.

It would seem from this description, brief as it is, that the classification of calls by northern bullfrogs is interpretable in terms of a set of defining features (sensory in nature) and rules for their relationship. However, the lack of information on the effect, if any, of experience in modifying call classifications, means that we have no independent assessment on whether an active selection process is involved.

5.3.7 Frog-Call Recognition by Bats

Another, possibly more sophisticated, example of call recognition, is that which is displayed by the frog-eating bat. It has been demonstrated that this bat uses frog calls not only as a means of locating its prey, but also as a means of discriminating between frogs of different sizes and palatibilities (Ryan & Tuttle, 1981). A further study by Ryan & Tuttle (1983) followed up their earlier demonstration that in a simultaneous choice test, the bats will avoid the call of the poisonous toad Bufo typhonius. In this study, they were attempting to determine whether the discrimination between poisonous and non-poisonous prey was a definite (i.e. either/or) discrimination or whether the calls were assessed in a graded fashion, perhaps on the basis of similarity to the call of B. Typhonius.

In the experiment, pairs of novel frog calls which to the researchers' formed a continuum of increasing similarity

to B. Typhonius, were used. The preferences showed by the bats in simultaneous choice tests were completely in agreement with the similarity judgements, suggesting that, not only is call preference based on similarity to B. typhonius calls, but the bats are assessing similarity in a manner like that of humans. The actual basis of that similarity is obscure, although temporal properties of the calls seem to be of primary importance. Acoustical analysis of the calls revealed no clear patterns.

In summary, it would appear that call recognition in the frog-eating bat is based on spectral characteristics, probably principally of a temporal nature; but that these properties cannot be thought of (as the previous example was) in terms of defining features and rules for their relationship. Instead, it seems likely that a more 'probabilistic' cluster of properties forms the basis for recognition - a recognition based on similarity assessments, and influenced by contextual cues (note the implication of these results, that the bat's response would be affected by other calls, if frogs of more than one species were calling at the same time).

5.3.8 Comparison of Processes of Call Recognition in Different Animal Species

Four examples of the diverse capacities for call recognition that exist among different species, have been given. The first, that of bat-call recognition in nocturnal moths, is an example of an adaptive, instinctive behaviour which is based on a beautifully simple feature-detector system.

The example of how the northern bullfrog recognizes its conspecifics' mating call, demonstrated a process which

requires some central involvement, and which is probably interpretable in terms of defining features and rules.

The frog-eating bat on the other hand, appears to be capable of assessing the calls of different species of frog and toad, in terms of their similarity to the call of a particular poisonous toad. This similarity judgement does not appear to be based on defining features, but appears to be like that found in humans, that is, based on similarity judgements.

5.4 DISCRIMINATION IN ARTIFICIAL TEST SITUATIONS

Much of the work in the field of animal discrimination has consisted of behavioural experiments designed to determine which features of shapes are detected and used to classify the shapes as the same or different from one another. Basically, these experiments involve matching-to-sample tasks, oddity tasks, or a combination of both (i.e. the animal is required to respond to two stimuli being the 'same' or 'different'). There are two approaches commonly used to determine the discrimination abilities of animals; the first involves training the subject to respond to a positive stimulus given a choice of two stimuli (using operant conditioning techniques), and comparing the rates of learning of different pairs of discriminations. The second involves the use of transfer tests, i.e. tests of the discrimination demonstrated between novel stimuli on the basis of cues learned in an earlier discrimination. The first of these demonstrates the relative ease of learning different discriminations, but it is the second which is more informative regarding the classification of stimuli as 'same' or 'different'.

Studies of shape discrimination have been carried out on fish, octopi, birds, rats, cats, primates, and other mammals. Unfortunately, research has not been carried out in such a way that a systematic comparison of species differences and similarities is possible. However, some of the characteristics of discrimination in a few different animal species are discussed below.

5.4.1 Shape Discrimination in Goldfish

The discrimination abilities of goldfish have been studied in a reasonably systematic and extensive manner (see Mackintosh & Sutherland, 1963; Bowman & Sutherland, 1969a; Sutherland & Bowman, 1969b; Sutherland, 1969; and Bowman & Sutherland, 1970). The experiments involved training the goldfish to respond to one of a pair of shapes, and, when the goldfish had reached criterion (usually 90% correct responses), replacing the stimuli with a variety of transfer shapes. The main points of interest are:

(i) goldfish tend to give much greater significance to differences in features in the top halves of shapes than those in the bottom halves;

(ii) when the stimuli were changed from black on a white background to white on black (or vice versa), transfer was good but not complete;

(iii) better transfer was evidenced when the size of the stimulus was increased rather than decreased, and an increase of four times the original stimulus lead to performance better than that to the original stimulus;

(iv) transfer occurred when some shapes were rotated but not on others (e.g. transfer occurred when 'W' and 'V'

shapes were rotated 90° or 180°, but did not occur between a square and a diamond);

(v) the discrimination of shapes whose point of difference is a horizontal vs vertical orientation is significantly easier than that of shapes which have oblique contours (i.e. oriented at 45° & 135° angles), but both are discriminable;

(vi) transfer occurred from square to horizontal and vertical rectangles, but not to oblique rectangles; likewise, transfer occurred from diamond to oblique rectangles, but not to horizontal or vertical ones (confirming that the orientation of the contours is a significant feature for goldfish); and

(vii) goldfish showed significant transfer to an outline parallelogram when presented with a circle, but gave no significant transfer to an outline square presented with a circle (but note that goldfish discriminated more readily between the original parallelogram and the circle than between the original square and the circle).

5.4.2 Comparison with Rats and Octopi

A comparison of discrimination in goldfish with that in rats and octopi (see Sutherland, 1969), indicates a number of interesting similarities and differences. Thus, transfer to smaller and larger shapes was evidenced by all three species, but whereas rats demonstrated a significantly better transfer to a large parallelogram than to a small, and no significant difference in transfer between a smaller and a larger square; octopi transferred better to a larger square than a small,

and on a smaller parallelogram than a large. Goldfish on the other hand, showed a tendency to respond like rats, but the difference in performance did not reach significant levels.

Pairing a vertical and horizontal rectangle demonstrated a tendency in rats, as in goldfish, to treat the horizontal rectangle as the original parallelogram and the vertical rectangle as the original square if trained on the horizontal parallelogram (vice versa if trained on the vertical parallelogram). In successive tests however, the rats trained on the vertical parallelogram showed excellent transfer from the square to a parallelogram with long side horizontal but no transfer at all to a parallelogram with long side vertical, while the other group of rats showed little transfer to either. It seems therefore that rats do not classify either horizontal or vertical rectangles as equivalent to the original parallelogram, but that on simultaneous presentation the rectangle oriented similarly to the shape on which the rat was trained, appears less like a square than the alternate rectangle. Octopi on the other hand, do tend to categorize horizontal and vertical rectangles with the original parallelogram rather than the square.

The results of tests with several different pairs of shapes indicate that rats learn the orientation of the oblique lines in the parallelogram and discriminate shapes containing oblique lines of the same orientation from ones with lines rotated through 90^{o}. Octopi however, did not appear to find this property significant. The results of the tests with goldfish indicated that the orientation of oblique contours was significant for them, but not to the extent that it was for rats.

Both rats and octopi tend to classify circles and diamonds with squares as opposed to parallelograms, with circles being significantly more easily confused with the square than is the diamond. Goldfish in contrast, more readily confuse the circle with the parallelogram. They also tend to confuse the circle with the square, but not at a significant level.

Transfer to an outline square and parallelogram was good but not complete in rats, with a tendency to be better to the parallelogram than the square. In octopi however, while similar results were obtained in simultaneous testing, in successive tests they demonstrated almost perfect transfer to the outline parallelogram but none at all to the square. Results of the tests with goldfish suggest that, like rats, they transfer better to outline parallelograms than squares, but the results were not conclusive.

5.4.3 Characteristics of Shape Discrimination in Animals

Experimental evidence indicates that many species are able to classify a shape as the same over a considerable range of size change. However, the extent to which size change is significant appears to vary across species, and across types of shape within species. It also appears that this capacity is innate and not a function of eye movements (see Ganz & Wilson, 1967).

While there is some tendency to transfer when the brightness of a shape and its background is reversed, it appears to occur less often as shapes become less simple.

While many animals successfully transfer a learned discrimination from filled-in shapes to outline shapes and

vice versa, it seems that this ability exists in different species in varying degrees, and that the success and degree of transfer is a function of the type of shape.

Although many species demonstrate some equivalence between a shape and its mirror-image, rotated shapes are not always treated as equivalent. While the recognition of some shapes when rotated is less disturbed than that of other shapes, the degree of rotation also appears to be a significant factor.

Significant differences between species concerning which shapes are treated as equivalent are clearly demonstrated, and the obvious conclusion is that different features are significant for different species. This is supported by the evidence that different species attend to different areas of a pattern. However, the possibility must be admitted that apparent species differences may be a function of differences in experimental design, the importance of which is indicated by the finding that different results are recorded depending on whether differential or nondifferential training, and if differential whether interdimensional or intradimensional training, is given. Results are also clearly influenced by a host of other methodological distinctions, such as whether presentation of stimuli is successive or simultaneous, and whether reinforcement is continuous or intermittent.

Many animals exhibit interocular transfer (i.e. a shape discrimination learned using one eye successfully transfers when the other eye is used). Additionally, intra-retinal transfer has been demonstrated in goldfish (Cronly-Dillon, Sutherland & Wolfe, 1966).

These characteristics point out the phenomena that

must be explained by any adequate theory of pattern recognition. Following Sutherland (1968) we may list nine conditions that must be fulfilled by such a theory (note that these conditions are not exhaustive):

(i) size invariance - why discrimination can successfully transfer when the sizes of shapes are altered, and also why the transfer is better for some sizes and shapes than others;

(ii) retinal position - how a discrimination learned via one part of the retina is transferred to another part (and relatedly of course, how interocular transfer occurs);

(iii) brightness invariance - what governs whether or not brightness reversal will allow transfer;

(iv) equivalence of outline and filled-in shapes - why do some shapes transfer better than others when reduced to an outline and how does it occur at all;

(v) non-equivalence of rotated shapes - what governs whether or not a rotated shape will transfer;

(vi) confusions between shapes - why are some shapes, quite dissimilar to humans, treated as equivalent by some other species;

(vii) jitter - what allows an animal to disregard varying degrees of distortion of a shape, and what is the extent of variation permissable before the shape cannot be identified;

(viii) segmentation - while very little work has been done specifically on the ability of non-human species to segment a pattern (but see Cerella's study quoted in 5.4.5) work done with humans implies it is important for pattern recognition;

(ix) physiological evidence - naturally, any theory of pattern recognition requires to be compatible with the physiological evidence.

The theory of pattern recognition proposed by Sutherland (1968) is that "animals store a highly abstract description of the input shape". The invariances evidenced in shape recognition make it clear that this process cannot be explained solely by the feature extractor mechanisms discovered by Hubel & Wiesel (Sutherland, 1969). Sutherland suggests that two distinct stages are involved. The first is the extraction of local features (such as segments and edges lying in particular orientations), together with preservation of spatial relationships by retinotopic mapping. The second is the forming of a rule describing the shape in terms of its local features (e.g. "H" can be described as two vertical lines of equal length with their midpoints joined by a shorter horizontal line) - a rule which expresses how the features are combined. "Since the same shape can be described by many different rules, the process of rule formation will contain elements akin to induction." (Sutherland, 1969)

Species differences in feature detectors or in the way rules are formed, are considered to be responsible for the differences in experimental results between, for example, octopi and goldfish. Thus Sutherland suggests that rats discriminate mainly in terms of the presence vs absence of oblique contours in a particular orientation in the lower half of shapes, while octopi discriminate mainly on the basis of the presence or absence of thin horizontal or vertical segments (where 'thin segment' refers to any part of a shape where two edges are separated by only a small gap). Goldfish

on the other hand, seem to rely heavily on the presence vs absence of oblique contours but their orientation is not signficant to them. The presence or absence of horizontal and vertical segments is also of some significance to them.

However, it is noted that, while the shape discrimination experiments provide clear evidence that goldfish can readily detect differences between two shapes that are only a matter of detail, octopi readily discriminate between shapes whose main masses are differently distributed, but are poor at discerning details. Sutherland interprets the clear difference in the way goldfish and octopi encode visually presented patterns, as reflecting phyletic differences in feature detectors or in the way rules are formed. However, it appears equally (and maybe more) valid to suggest that there are in fact fundamentally different processes going on in the two species.

It also seems that the design of the experiments begs the demonstration of this type of process. A number of experiments undertaken in the laboratory in recent years, have looked at the ability of non-human animals (specifically, pigeons) to recognize ill-defined categories. A discussion of this evidence is preceded by a brief look at the results of some of the tests of shape discrimination carried out on pigeons.

5.4.4 Shape Discrimination in Pigeons

The transfer of a learned discrimination between a triangle and a square to figures which vary in systematic ways was investigated by Towe (1952). His principal findings were that:

(i) the discrimination did not transfer to rotated figures;

(ii) transfer did occur when the cues were reduced by removal of a segment from the figures, except that reduction to dot figures resulted in a failure to transfer;

(iii) transfer occurred when the size of the figure was altered (although a tendency to prefer the larger figure was observed);

(iv) the discrimination transferred when the brightness was reversed; and

(v) transfer occurred to a variety of distorted figures.

The affect of altered orientation of pigeons' recognition of stimuli as 'same' or 'different' was investigated in greater detail by Reynolds (1961). In this study, pigeons were trained to respond to an upright isosceles triangle, and then given transfer tests using systematic rotations of the triangle. Reynolds found that pigeons did transfer to rotated figures, and performance was better to rotations of 160° to 200° than to some intermediate values (e.g. 90° to 130°).

Similarly, Vetter & Hearst (1968) investigated the discrimination of rotated parallelograms, following Rausch's discovery (1952) that humans perceived changes in shape with the rotation of a parallelogram, and that parallelograms with horizontal and vertical diagonals were perceived as similar while those with two horizontal or vertical sides were placed in another group (note that parallelograms of the former group are much further apart from each other in terms of tilt than a parallelogram from each group would be). In Vetter & Hearst's study, it was found that, while non-differential training produced little stimulus control along the dimension of orientation, pigeons whose training had included trials

in which the parallelogram was absent, responded to orientations of 0^{o} (i.e. the orientation of the training stimulus), -90^{o} and $+90^{o}$ much more than to orientations of $-+40^{o}$ and $-+50^{o}$. This discrimination between parallelograms with horizontal and vertical diagonals (0^{o}, $+/-90^{o}$) and those with two horizontal or vertical sides ($+-40^{o}$, $+-50^{o}$) echoes Rausch's finding. It is interesting however, to note that the unimodal generalization gradient supposedly typical of an animal's responses to changes along a physical dimension (as opposed to the bimodal generalization gradient found in Vetter et al's experiment), could be produced by specific discrimination training along the orientation dimension (intradimensional training).

These experiments clearly indicate that degrees of angular rotation is not a sufficient or appropriate stimulus dimension in terms of rotational invariance. One possibility that Vetter & Hearst put forward was that the position of the vertices may be a relevant stimulus dimension for pigeons in parallelogram rotation. This possibility was investigated by Ferraro & Grisham (1972). They demonstrated that the distance of vertices movement from the training stimulus did indeed correlate with the speed of discrimination learning, and that the direction of vertices movement was also significant. However, stimulus control along a dimension of the distance of vertices movement depended upon prior intradimensional training.

5.4.5 Natural Concepts in Pigeons

There is another way of looking at the results of the experiments into shape discrimination in pigeons however, and that is, to note that the transfer, where it occurs, is not

complete. Vetter & Hearst's study tells us that rotation does make a difference; Wildemann & Holland (1973) looked at the effects of altering size using a circle as training stimulus, and found responses to the altered stimuli were lower; Heinemann & Kadison (1976) found that varying the location of the stimulus (a spot) disrupted the pigeon's recognition of the pattern.

It appears then, that these alterations of size, rotation and position, are significant to the pigeon. Such data may be interpreted as suggestive of a template-matching system (Cerella, (1982). However, investigations into the ability of a pigeon to disregard these alterations have not supported this view (see, e.g., Blough's (1979) finding that pigeons can discriminate the letter 'O' from the letter 'X' across 16 stimulus locations; and Morgan, Fitch, Holman & Lea's (1976) evidence for successful discrimination of the letter 'A' and the digit '2' across 18 different typefaces).

The suggestion has been made (see Cerella, 1982) that pigeons can form a prototype by averaging a number of exemplars, and then use this prototype to identify new exemplars. Cerella reports that, when the training stimuli were random distortions of two prototypes (a square and a chevron), pigeons' responses to individual patterns indeed varied with their distortion from the prototypes. The use of 'natural concepts' as stimuli in tests of discrimination provide an approach which may help answer this question.

An initial study (Herrnstein & Loveland, 1964) involved the training of pigeons (using operant conditioning techniques) to respond to the presence or absence of human beings in photographs. Over 1200 colour slides of natural

settings were used, and in each session about half the slides included at least one human being. The experimenter could not find any other systematic way in which the slides varied. Using rate of pecking as a measure of whether the concept was learned, all five subjects showed a significant differential response towards the two classes of slides.

This study was extended by Siegel & Honig (1970), who confirmed that pigeons demonstrated a discrimination learned on the basis of a variety of positive and negative stimuli, and transferred the discrimination to novel stimuli. The discrimination apparently could be learned using either simultaneous or successive presentation, and was maintained in tests where the pictures were inverted (i.e. rotated 180^{o}) but not in tests wherein the picture was displayed out of focus (thus blurring the contours but maintaining the distribution of colour).

Reasoning that the concept of 'pigeon' would be more salient than that of 'human' to a pigeon, Poole & Lander (1971) investigated the pigeon's concept of 'pigeon'. As expected, the discrimination was learned very rapidly and more efficiently than that of 'human'. Indeed, the speed with which the discrimination was learned makes it clear that it was only the nature of the task, rather than the concept itself, that was required to be learned.

It was also found that pictures of other birds were responded to more often than that of other negative stimuli, implying that there were some shared characteristics between birds and pigeons, but that, as the response to pigeons was significantly better than that to other birds, the concept of 'pigeon' was more specific than that of 'bird'. It is

also worthy of note that the concept was flexible enough to include fancy varieties of pigeon.

In an effort to determine the minimal number of exemplars needed for a pigeon to learn the 'people' concept, Malott & Siddall (1972) used serial presentation (a design which uses discrete trials and continuous reinforcement, as opposed to the free operant design with intermittent reinforcement which characterized the earlier studies). The results of this study indicated that a pigeon requires some 3 to 17 positive and negative exemplars to reach the criterial level of discrimination, and showed that pigeons can rapidly form a complex concept using this experimental design.

The ability of pigeons to form more complex concepts than that so far demonstrated, was investigated by Lubow (1974). The discrimination used was that between man-made objects and non-man-made objects, and the main point of interest is Lubow's finding that, if the pigeons were discriminating on the basis of (a) presence of straight lines and/or 90^{o} angles, and (b) light and dark areas, plus high contrast between them, plus half-and-half light-and-dark, then only 2 - 8% of the positive stimuli were unaccounted for.

Other studies since then have demonstrated the pigeon's ability to discriminate trees, bodies of water, a particular woman (Herrnstein, Loveland & Cable, 1976; Herrnstein, 1979), oak leaves (Cerella, 1979), and fish (Herrnstein & de Villiers, 1980).

The interpretation of this research has not proved non-controversial. Herrnstein has taken the position that such discrimination abilities clearly demonstrate the holding of "highly numerous or infinite stimulus classes"

(Herrnstein, 1979), and thus suggests the usage of underlying rules for classification rather than simply a set of defining features.

As possible classification rules, he suggests those based on stimulus similarity (in the sense of proximity along standard physical dimensions). Lubow's study provides support for this. However, Herrnstein regards the ability of pigeons to correctly classify novel instances of trees, people, and oak leaves, as evidence that categories are not only, or all, formed on the basis of proximity on physical dimensions.

This interpretation has not gone unchallenged. In particular, the assumption that classes such as 'trees' are not discriminable on the basis of a few common elements (presumably isomorphic with single neuronal units), has been questioned (see Premack, 1983). However, we may note that no-one has yet suggested a credible set of defining features upon which the demonstrated discriminations might be made.

On the other hand, Cerella (1982) reports an experiment in which pigeons failed to demonstrate a discrimination based on the concept of 'tree'. Initially, the researcher (Anish, 1978) trained pigeons to identify a single positive stimulus (a colour slide of a tree), using a variety of outdoor (tree-less) views as negative stimuli. No response to any of the test stimuli was evidenced. Anish followed this up with an experiment in which the training stimuli included several positive patterns, each slightly different. One group of subjects were trained on positive stimuli which shared the characteristics of being full-length views of medium-sized trees; the other group trained on close-up views of leaves

and twigs. When the pigeons were tested, it was found that the pigeons in each case responded to those test stimuli which were physically similar to the training stimuli, i.e. were full-length views of medium-sized trees, or close-up views of leaves and twigs (note how this relates to the finding of different effects following intradimensional vs interdimensional training, 5.4.4.).

Cerella himself suggests that, in the light of this evidence, the results of the experiments using natural concepts may be understood by hypothesising that such concepts are defined in terms of a set of "focal instances" (e.g. "male, front view, full figure, middle ground") and that subsets of physically similar instances surrounding each focal instance are reachable by a process of flexible template-matching (although the idea of a flexible template implies a use of the word 'template' which is uncommon). The problems of how such properties as 'male' might be encoded, and what is meant by 'physical similarity, are glossed over by Cerella. Instead, he seems to regard the key issue as the flexibility of the template-matching process, i.e. how many exemplars are 'covered' by a single template in relation to the total class; thus, how many templates are needed to represent a concept?

Studies using artificial concepts may throw some light on this issue. One study (Cerella, 1982) investigated the ability of pigeons to identify pictures of the cartoon character Charlie Brown, from pictures of the other characters in the same cartoon strip. Test stimuli included incomplete, scrambled (i.e. Charlie Brown was divided into three parts and the segments rearranged) and inverted images, as well as

complete but novel instances. The recognition of scrambled instances in particular appears to rule out a template model. Cerella consequently modified the model to use local rather than global templates. This is a misleading use of terms, because what he in fact has done is replace a template model with a feature-detector model. Still, the important point is that Cerella's experiment can be taken as support for the position that pigeons decompose patterns into sets of local features. The question of whether or not pigeons were aware of relationships between features was also investigated by Cerella (1977; 1979), who concluded on the basis of his experiments that they were not. However, the results of these experiments cannot, as he himself admits, be taken as conclusive, owing to various limitations of the stimuli used.

Despite this evidence from Cerella, who seems, in the writer's opinion, to strain the data somewhat in attempting to find an explanation which is more in keeping with a passive, feature-extractor assumption, the evidence seems to support the view that pigeons are capable of classifying stimuli in a flexible manner. There does not appear to be any justification for different interpretations of similar behaviours demonstrated by humans and pigeons.

5.5 CONCLUSIONS

In the evolution of intelligent behaviour, we may see two paths. The first involves the development of an ability to infer rules which express the way in which features - also inferred as significant (rather than extracted as a function

of only having the appropriate 'feature extractors') - are combined. This has been termed the 'definitional' cognitive process, and its evolution is seen as being an extension of the mode of perceptual processing termed the 'stimulus summation process'. Thus, we can see a development from:

(i) recognition of some functional classes (especially those involved in inflexible, stereotyped, 'instinctive' behaviours) as a function of passive coding mechanisms (in which, by the use of serial, progressively more complex, coding steps, recognition is by a one-to-one matching of 'releasing stimulus' with a single unit responsive to a stimulus isomorphic with that external stimulus); to

(ii) recognition of some functional classes as a function of a simple summation process, in which features isomorphic with single units in the processing system are independently processed and integrated by a simple additive combination - a process which is again, essentially passive; to

(iii) recognition involving the active selection of significant features (isomorphic with single units and independently processed) and induced rules for how these features are combined.

On the other hand, the change in the nature of the feature implicit in the development of a Gestalt perceptual process, led to a different path. On this path, we can see the early development of an active selection process, as a consequence of the development of a capacity to learn from one's experiences. Given the ability to select what features

are significant, the ability to learn to perceive certain complex stimuli as "integrated wholes" rather than having to analyse them step-by-step, could develop. The advantages accruing to such a process - particularly in terms of reduced processing time - made such a development inevitable once it was possible. However, the ability to perceive complex stimuli holistically is problematic for the information-processing system. The holistic representation of stimuli is not processable by a 'definitional' cognitive process. Given holistic representations, the necessity to assess stimulus classifications on the basis of perceived 'similarity' seems clear. Hence, the development of a 'probabilistic' cognitive process seems inevitable, given the use of Gestalt perceptual processing.

CHAPTER 6

DISCUSSION

6.1 THE NATURE OF INTELLIGENCE

As we said in Chapter 2, what 'intelligence' means is a matter of definition; accordingly we may say that intelligence is "the ability to understand, reason and perceive; quickness in learning, mental alertness; ability to grasp relationships" (Penguin English Dictionary) with some assurance. From this known point however, the construction of more rigorous definitions becomes somewhat more conjectural. There are those who have attempted to define intelligence more precisely through tests of problem-solving abilities. Since it is self-evident (i.e. a matter of definition) that intelligence and problem-solving abilities are related in some way, it is hardly surprising that such a strategy has enjoyed some success in the purely practical matter of making limited predictions, on the basis of some assessed 'level' of intelligence. In other areas, and particularly in its explanatory power (none), the approach has proven inadequate.

Some researchers maintain that intelligence should be defined simply as the ability to learn. Certainly "no-one would want to argue that learning ability is not a component of intelligence" (Hunt, 1980). However, it seems clear from consideration of our 'intuitive' evaluations of various behaviours in non-human animals, that learning,

while no doubt highly correlated with intelligence, is not of itself a sufficient basis for the judgement that intelligence is being demonstrated.

In the more general question of intelligence among animals, rather than the specific one of the precise nature of human intelligence, we find that ethologists tend to describe behaviour as intelligent on the basis of its adaptive value and flexibility. The evaluation of intelligent behaviour on the basis of observable characteristics is without doubt a functional one, but it appears to be considerably removed from the meaning of intelligent as it is generally understood.

Intuitive judgements of the behaviours of non-human animals have led the writer to postulate that the presumption of qualities such as purposiveness, judgement and choice, underlies our ascription of intelligence to behaviour. In some way, the selection of a course of action in any situation is presumed to be different in animals considered 'intelligent' from that of animals considered 'non-intelligent'.

In the general context of "the organism as an information-processing system", which approach is assumed in this text, it seems reasonable to postulate that this difference has to do with the selection of the information which is used in 'deciding' what action to take. More specifically, it seems that the basis for the ascription of intelligence to behaviour, is the judgement that the organism is actively selecting the body of information (stored and situational) which is significant. In contrast, the selection process could be passive - determined by aspects of the input system, and automatic processing upon the input.

6.2 THE SELECTION OF SIGNIFICANT INFORMATION

In any situation, there is a vast amount of information. To the animal in the situation, faced with the need to make some sort of behavioural response, some of this information is significant (that is, it will assist the animal in 'deciding on' an appropriate response), and some of it is not. To the common tick, waiting on a bush for a passing mammal, only two pieces of information are significant - a temperature of around 37^{o}C and a smell of butyric acid. When these criterial features are observed in conjunction, the tick responds appropriately. One may speak of the tick's functional classification of 'mammal', but it is readily apparent that, although the classification is explicable in terms of 'definitional' theory, the process does not warrant the description of 'cognitive'. This is because the process is a purely mechanical one - the extraction of the significant information is a function of an extremely limited sensory system.

On the other hand, it is clear that many animals - birds and mammals in particular - have sensory systems capable of detecting a substantial amount of the information inherent in any situation. Humans for example, appear to have a memory system that holds a detailed image for a very brief time, of the information received at a particular sense organ. This "sensory information store" stores more information than can be extracted, implying that there are limits on the capacity of later stages - limits not shared by the sensory stages themselves (Lindsay & Norman, 1972). Accordingly, it becomes necessary to postulate some top-down process which sorts this information into significant and irrelevant.

However, while the use of an active selection process may be a requirement for intelligent behaviour, there is rather more to the processing of information than the selection of the information to be processed.

6.3 THE PROCESSING OF PERCEPTUAL INFORMATION

As Dodwell (1978) says: "..the ability to discriminate between different two-dimensional shapes may seem a simple matter, yet it cannot be understood in terms of an ordered set of physical parameters: the perceiving system itself must impose order where none is intrinsic to the stimulation - or not obviously so. Similarly (conceptual) categorization... can be simple or complex, but again implies the active engagement of the organism in the perceptual process".

It is evident that even at the first level of perceptual processing, there is rather more to the processing of stimuli than is involved in the traditional, reductionist approach, in which stimuli are assumed to be broken down into features isomorphic with single units in the input system.

Some of the evidence relating to human processing at the levels of signal detection and pattern recognition, which challenges this approach (from Chapter 4), is summarized:

(i) stimuli which may be defined as changes on (measurable) sensory dimensions, may be processed either holistically (as an integrated whole) or analytically (by independently processing separate elements of the stimulus); which mode of processing is used is not purely determined by the nature of the stimulus, but is also governed by processor and task variables;

(ii) the use of holistic perceptual processing implies that in some situations, analysis may be less efficient or even inappropriate - holistic processing is faster, and puts less demand on the processing system; it is also probable that in some situations, the analysis of interdependent elements will lose significant information;

(iii) at the level of pattern recognition, the illusory contours which are perceived by human observers in certain situations, and 'explained' by the Gestalt principles of organization, provide clear evidence that there are processes involved which are considerably more complex and globally organized than the extreme feature detector theories would suggest;

(iv) a growing body of neurophysiological evidence supports the view that spatiotemporal patterns of neural activity are the basis of information processing, rather than single units;

(v) there is evidence that, while local feature analysis may occur in the striate cortex, in the extrastriate cortex processing involves global configurations;

(vi) configurational perception is indicated as being a precursor to local feature analysis, in that it organizes the data being received in the system, and selects data worthy of more detailed study; and

(vii) a brief review of pattern recognition theories suggests that geometrical models - in which visual space is postulated as having a geometry and structure of its own, which governs the representation of

objects, and which emphasises the potentially holographic nature of those representations - may accurately express part of the human information-processing system.

In the study of these two levels of perceptual processing, we may see a basic distinction in what may be termed the traditional or analytic approach, and the configurational or holistic approach. In the former, we see an assumption that any stimulus is composed of elements that may be functionally defined as those stimuli which are objectively measurable in terms of a single physical dimension. Moreover, it is assumed that in processing perceptual information, stimuli are broken down into these elements and processed separately, to be recombined later according to some automatic additive process. On the other hand, the holistic approach emphasises the interdependence of elements. If, as Gestalt theory declares, "the whole is greater than the sum of its parts", then it is clear that separate processing of interdependent elements will give a different 'answer' than integral processing.

However, in emphasising the evidence for global processing, the importance of analytic processing must not be overlooked. It has been clearly demonstrated that "coherent pattern analysis breaks down in the absence of... critical features" (Dodwell, 1978). It is only because the case for featural analysis is so well-established that the discussion has focussed on the evidence that such analysis is not the <u>whole</u> story.

6.4 USING PERCEPTUAL INFORMATION FOR COGNITIVE ENDS

The basic distinction between analytic and more holistic modes of processing is echoed at this level of processing. The classical or definitional approach to human categorization assumes that categories are represented, and category members recognized, on the basis of necessary and sufficient defining features, which are ultimately decomposable into elements (as defined above). Similarly, it is assumed that processing of the constituents is independent, and that recombination is a matter of some automatic additive process.

This traditional view has been modified somewhat over the years, to make allowance for the more active involvement of the human processor. Accordingly, the original emphasis on the passive learning of significant features (through the arbitrary association of stimuli in the processor's experience), changed to an emphasis on the learning of rules for the combination of those features. The accepted approach was that these rules were learned through a process of active hypothesis-testing.

On the other hand, recent theories of categorization have assumed that there is "..no logical rule or set of criterial features that is used to determine category membership. It has therefore been assumed that some probabilistic or holistic rather than analytical or logical process is used for determining category membership" (Martin & Caramazza, 1980).

Research into categorization processes in humans has uncovered a great deal of evidence which, in the context of these opposing approaches, appears contradictory. It seems

reasonable to suggest however, that the contradictory evidence is more likely to reflect faults in the theoretical framework within which it is interpreted, than major inaccuracies in the evidence. For example, there can be no doubt that humans, in certain circumstances, attempt to form rules by which stimuli can be categorised. Yet, with the rise of probabilistic models, we see many researchers simply ignoring this evidence. The argument seems to be that, if you can show that something (like rule-learning) doesn't happen in some cases, then you have shown that it never happens.

The main points of the empirical evidence relating to how stimuli are classified and concepts formed, are summarized:

(i) evidence of graded responses to category members is
   (a) interpreted to mean that category members are differentially representative of the category; and
   (b) interpreted as challenging definitional theory, which states that category members are defined by singly necessary and jointly sufficient features, and thus implies that all members are equally representative of the category.

   These interpretations are challenged by evidence that graded responses are found for categories assumed to be well-defined, and by the observation that graded responses may reflect the continuous (rather than discrete) nature of the component properties;

(ii) evidence that category judgements can vary between people, and across time and context within individuals is

(a) interpreted to mean that category boundaries are 'fuzzy', i.e. not clearly defined; and

(b) interpreted as challenging definitional theory, which implicitly states that categories are well-defined;

(iii) evidence that people, when asked to list category exemplars, list attributes not possessed by all exemplars of a category is

(a) interpreted to mean that people use non-necessary (i.e. characteristic) properties in classifying stimuli; and

(b) interpreted as challenging definitional theory, which states that categories are defined by necessary properties only;

(iv) evidence that stored exemplars are used in making category judgements is

interpreted as challenging both definitional and probabilistic theories, which state that category judgements are made on the basis of information contained in summary representations; and

(v) evidence that both specific exemplars and summary representations are used in making category judgements is

interpreted as challenging all 'pure' theories.

Additionally, there are a number of more theoretical issues, of which the following are important for the present discussion:

(i) definitional theory is challenged by the evidence that even well-defined concepts cannot be made to break down into defining component properties;

(ii) probabilistic and exemplar theories are challenged by their failure to account for conceptual combination (the forming of complex concepts out of simple ones); and

(iii) exemplar theory is weakened by its implicit requirement for summary information, learned as such, to be stored with each exemplar of the category.

It seems clear that, for each of the general theories - definitional, probabilistic and exemplar - one can cite convincing evidence for and against. It is for this reason that the dual theory, in which concepts are represented by a (definitional) core description and a (probabilistic) identification procedure, is becoming popular among cognitive theorists. However, this overlooks the evidence for exemplars.

On the other hand, Medin & Schaffer's context theory may be thought of as a theory which 'mixes' probabilistic and exemplar theories. This theory enjoys some considerable success in accounting for phenomena of categorization, and has the added advantage of being the theory most compatible with recent theories of memory (see 6.5). It, however, overlooks the evidence supporting definitional theory.

It is possible that both of these theories express an aspect of the processing system. If, as Dodwell suggests, the complexity of the human visual system is such that no single model will be able to explain it (Dodwell, 1982), then how much more is this likely to be true of the entire

processing system? In broad outline, the evidence would seem to support the idea that there are two cognitive processes (which may, in certain circumstances, be related in a way that is expressible in the terms of the dual theory), which may be thought of as essentially 'definitional' or 'probabilistic' in nature. The fundamental assumption of the inductive nature of the processes, makes it clear that the forming of categories, whichever cognitive process is involved, requires the use of exemplars, at least in the initial stages.

A Tentative Solution to Problems of the Holistic Approach

It was said that the major reasons for the neglect of the holistic approach in theories of categorization, were (a) the number of representations required to be stored; and (b) the difficulty in accounting for how stored representations and real-world objects were compared. The beginnings of an answer to both these problems may perhaps be found in recent research into human memory.

In an increasingly popular approach to memory (see Hinton & Anderson, 1981; Wicklegren, 1981, for discussion and review of this approach), it is assumed that information is widely distributed so that many items are stored in the same neural units (implicit in the neurophysiological evidence referred to earlier). The essential nature of human memory as it is espoused in this approach, is that memory is associative and content-addressable. The direct access retrieval implicit in a content-addressable store allows parallel processing (as opposed to the serial search for information necessitated by a location-addressable store).

As Wicklegren notes, "The more one considers the difficulties of serial search retrieval processes for recognition of any of the tens of millions of things human beings can recognize in a matter of seconds, the more one appreciates the power of parallel processing, direct access retrieval systems" (Wicklegren, 1981). It is evident that the random serial search of a location-addressable memory store would be far slower than the parallel search of a content-addressable store - which by its nature also allows information to be retrieved on the basis of partial descriptions (Hinton & Anderson, 1981).

An associative, content-addressable memory is clearly faster, more efficient, and more flexible, than the type of serially-processed, location-addressable memory implicit in traditional processing assumptions. However, even some models which assume the storage of information is distributed, also incorporate local storage processes. It seems probable that in the question of local vs distributed memory storage, the type of information stored may be a confounding variable.

In this idea of memory being associative, processed in parallel, and content-addressable, we see support for both a probabilistic cognitive process and, more directly, for representations of a more holistic nature. Moreover, in the suggestion that two types of memory storage are used, we see indirect support for the existence of two cognitive processes.

6.5 THE EVOLUTION OF INTELLIGENCE

The existence of two cognitive processes corresponds

with the two modes of perceptual processing found at each of the lower levels of perception. It seems reasonable to suggest that, as with those processes, the employment of the cognitive processes is determined by a number of stimulus, processor and task variables. This argument is supported by evidence from studies of stimulus classification in non-human animals.

The evidence from shape discrimination experiments (in 5.4) makes it clear that processing is not explicable solely in terms of the type of feature extractor mechanisms postulated by Hubel & Wiesel. Instead, the evidence is interpretable in terms of 'definitional' theory. However, if there are two processes, the use of which is determined by task, stimulus and processor variables, then this experimental situation is clearly biasing the result. The situation is (deliberately) one in which an analytic, rule-learning process is required.

That this is in fact what has happened, is borne out by the experiments using natural concepts (discussed in 5.4.5). The results uncovered there, strongly suggest the importance of stimulus variables. The role of task variables too, is indicated in both shape discrimination and natural concept experiments - in which a host of experimental design factors are seen to affect the results.

It is unfortunate that the direct investigation of stimulus classification in non-human species, within the framework employed here, has been restricted to such artificial situations. Studies of more natural stimulus classification rarely answer the questions of interest to us. For this reason, all that can be provided is suggestive examples.

However, with this reservation, it seems reasonable to suggest that processing systems of diverse natures and capabilities can be found among animal species, and that some of these processing systems seem to be based on similar principles as those of humans.

As originally conceived, the classical definitional view of perceptual and conceptual categorization was an essentially passive process, not compatible with what we understand by 'intelligent behaviour'. Stimulus classifications which are based on this type of process may be seen in various stereotyped, species-typical behaviours, and may be termed 'discrimination' rather than 'categorization'. The development of coding mechanisms within the processing system has allowed (as suggested by Hubel & Wiesel) the processing of progressively more complex stimuli.

That this type of process may allow complex and adaptive behaviours, has been demonstrated in various examples (such as the leaf-cutting ant and the nocturnal moth). The inflexibility inherent in this system however, puts serious limits on the organism's ability to survive environmental change.

Jerison (1973) has suggested two important dimensions underlie intelligent behaviour:

(i) the extent to which specific sensory capacities have been developed as specific to adaptive niches occupied by a species; and

(ii) the extent to which behaviour in response to sensory information is flexible and adjustable to inconsistencies in that information.

We may relate this to a distinction that may be made between animals with narrowband sensory filters ('specialists') and those with wideband sensory filters ('generalists') (Ewert, 1980). Specialization allows stimulus identification to occur at the level of the receptor membrane (as in bat-call recognition in nocturnal moths). Wideband sensory filters on the other hand, do not allow stimulus identification to be a purely peripheral function. Generalists require a processing system of greater complexity.

It is also clear that specialized input systems are inadequate if the animal lives in a variety of subenvironments or a highly unpredictable environment (Ewert, 1980). It is the heterogeneity of the environment that demands systems capable of responding to a wide variety of sensory stimuli.

It was the increasing demands on the information processing system which led from the use of a processing system in which stimulus classification is based on single units responsive to 'releasing stimuli', to the development of a mechanism whereby the outputs of these single units can be combined according to some additive computation, and then to the development of a mechanism which allows the active involvement of the organism in the process. From this comes the evolution of the 'definitional' cognitive process, expressed in the active selection of significant features, and the formation of 'rules' for how those features are combined.

However, studies of perceptual and conceptual processes in animals uncover many examples of behaviours which do not seem readily interpretable within this frame-work. In particular, it seems evident that animals can

perceive complex stimuli as integrated wholes. Stimulus classification clearly doesn't always require an analytic process. If patterns and objects can be recognized without analysis, it implies that the stored representations are holographic in nature. The process whereby these holistically perceived objects are compared with these holographic representations is clearly not one which can be expressed in the terms of the 'definitional' approach. Instead, comparison must be on the basis of some similarity judgement, in line with the 'probabilistic' approach.

It is clear that this type of processing is considerably more flexible than the 'definitional' cognitive process. Moreover, it seems likely that the nature of the 'definitional' process is such as to put much greater limits on the capacity of the information processing system. Thus, it is postulated that; although a 'definitional' cognitive process can underlie intelligent behaviour, the capacity for intelligent behaviour is far less if the animal has this type of processing system only. In other words, the potential for intelligence is significantly greater in an animal who possesses a dual processing system.

It is probable that a dual processing system exists in most, if not all, mammals, birds and cephalopods. Animals who use a definitional cognitive process only, are probably found widely among fish and amphibians. Most invertebrates probably only possess a passive process.

It is not suggested that dual processing systems are all identical. As within the other broadly classified processing systems, the specific systems vary in complexity,

capacity or structure. The details must await research which is specifically directed towards this question. The evidence available at the present time is barely adequate to use as a basis for this speculative theory.

REFERENCES

Anderson, J.R. (1980). Cognitive psychology and its implications. San Francisco: W.H. Freeman & Co.

Anish, D.S. (1978). The natural concept tree: A study on learning in pigeons. Undergraduate Honours thesis, Harvard College.

Armstrong, S.L., Gleitman, L.R. & Gleitman, H. (1983). What some concepts might not be. Cognition, 13, 263-308.

Barlow, H.B. (1953). Summation and inhibition in the frog's retina. Journal of Physiology, 119, 69-88.

Benson, D.F. & Greenberg, J.P. (1969). Visual form agnosia. Archives of Neurology, 20, 82-89.

Bindra, D. (1976). A theory of intelligent behaviour. New York: John Wiley & Sons.

Blank, A.A. (1958). Analysis of experiments in binocular space perception. Journal of the Optical Society of America, 48, 911-925.

Blough, D.S. (1961). The shape of some wavelength generalization gradients. Journal of the Experimental Analysis of Behaviour, 4, 31-40.

Blough, D.S. (1979). Effects of number and form of stimuli on visual search in the pigeon. Journal of Experimental Psychology: Animal Behaviour Processes, 5, 211-223.

Bourne, L.E. (1982). Typicality effects in logically defined categories. Memory & Cognition, 10(1), 3-9.

Bower, T.G.R. (1966). Heterogeneous Summation in Human Infants. Animal Behaviour, 14, 395-398.

Bowman, R. & Sutherland, N.S. (1969). Discrimination of "W" and "V" shapes by goldfish. Quarterly Journal of Experimental Psychology, 21, 69-76.

Bowman, R.S. & Sutherland, N.S. (1970). Shape discrimination by goldfish: coding of irregularities. Journal of Comparative & Physiological Psychology, 72, 90-97.

Brooks, L.R. (1978). Nonanalytic concept formation and memory for instances. In Cognition and Categorisation. (Eds.) Rosch, E. & Lloyd, B.B., Hillsdale, N.J.: Erlbaum.

Brown, J.L. (1975). The evolution of behaviour. New York: W.W. Norton & Co.

Brzoska, J. & Schneider, H. (1978). Behavior Process, 3, 125-136. Cited in Ewert, J. (1980). Neuroethology. New York: Springer-Verlag.

Burns, B.D. & Smith, G.K. (1962). Transmission of information in the unanesthetized cat's isolated forebrain. In Journal of Physiology, 164, 238-251.

Caelli, T.M. (1974). Models, Lie algebras and visual pattern perception. Ph.D. dissertation, University of Newcastle, Australia.

Caelli, T.M. (1977). Psychophysical interpretations and experimental evidence for the LTG/NP theory of perception. Cahiers Psychologie, 20, 107-134.

Campbell, F.W. (1974). The transmission of spatial information through the visual system. In The Neurosciences: Third Study Volume. (Eds.) Schmitt, F.O. & Worden, F.G. Cambridge, Mass.: MIT Press.

Campbell, F.W. & Robson, J.G. (1968). Application of Fourier analysis to the visibility of gratings. Journal of Physiology, 197, 557-566.

Capranica, R.R. (1965). The evoked vocal response of the bullfrog: A study of communication by sound. M.I.T. Research Monograph, 33, 1-110.

Cerella, J. (1977). Absence of perspective processing in the pigeon. Pattern Recognition, 9, 65-68.

Cerella, J. (1979). Visual classes and natural categories in the pigeon. Human Perception and Performance, 5(1), 68-77.

Cerella, J. (1982). Mechanisms of concept formation in the pigeon. In Analysis of Visual Behavior. (Eds.) Ingle, D., Goodale, M. & Mansfield, R. Cambridge, Mass.: MIT Press.

Cronly-Dillon, J.R., Sutherland, N.S. & Wolfe, J.B. (1966). Intraretinal transfer of a learned visual shape discrimination in goldfish after section and regeneration of the optic nerve brachia. Experimental Neurology, 15, 455-462.

Darwin, C. (1904). The formation of vegetable mould through the action of worms with observations on their habits. London: John Murray.

Denny, M.R. (1980). Comparative psychology: an evolutionary analysis of animal behavior. New York: John Wiley & Sons.

Dineen, J. & Keating, E.G. (1979). Demonstration of complex pattern vision in the monkey completely lacking striate cortex. Society for Neuroscience Abstracts, 5, 782.

Dodwell, P.C. (1970). Visual pattern recognition. New York: Holt Rinehart Winston.

Dodwell, P.C. (1978). Human perception of patterns and objects. Handbook of Sensory Physiology VIII Perception. (Eds.) Held, R., Leibowitz, H.W. & Teuber, H. New York: Springer-Verlag.

Dodwell, P.C. (1982). Geometrical approaches to visual processing. In Analysis of Visual Behavior. (Eds.) Ingle, D., Goodale, M. & Mansfield, R. Cambridge, Mass.: MIT Press.

Drees, O. (1952). Untersuchungen über die angeborenen Verhaltensweisen bei Springspinnen (Salticidae). Zeitschrift fuer Tierpsychologie, 9, 169-209.

Dru, D., Walker, J.P. & Walker, J.B. (1975). Self-produced locomotion restores visual capacity after striate lesions. Science, 187, 265-266.

Erickson, R.P. (1963). Sensory neural patterns and gustation. In Olfaction and taste. (Ed.) Zotterman, Y. New York: Pergamon Press.

Ewert, J. (1980). Neuroethology. New York: Springer-Verlag.

Ewert, J. (1982). Neuronal basis of configurational prey selection in the common toad. In Analysis of Visual Behavior. (Eds.) Ingle, D., Goodale, M. & Mansfield, R. Cambridge, Mass.: MIT Press.

Ewert, J. & von Seelen, W. (1974). Kybernitik, 14, 167-183. Cited in Ewert, J. (1980). Neuroethology. New York: Springer-Verlag.

Faley, R.H. & Alkon, D.A. (1985). Cellular mechanisms of learning. Annual Review of Psychology, 36, 236-269.

Ferraro, D. & Grisham, M. (1972). Discrimination and generalization of complex visual shape variations in pigeons. Perceptual & Motor Skills, 35, 915-927.

Foard, C.F. & Nelson, D.G.K.(1984). Holistic and analytic modes of processing: The multiple determinants of perceptual analysis. Journal of Experimental Psychology: General, 113(1), 94-111.

Fodor, J.A., Garrett, M.F., Walker, E.T. & Parkes, C. (1980). Against definitions. Cognition, 8(3), 1-105.

Fodor, J.A. & Katz, J.J.(1963). The structure of a semantic theory. Language, 39, 170-210.

Forster, L.M. (1979a). Visual mechanisms of hunting behaviour in Trite planiceps, a jumping spider (Araneae: Salticidae). N.Z. Journal of Zoology, 6, 79-93.

Forster, L.M. (1979b). Comparative aspects of the behavioural biology of some N.Z. jumping spiders. Ph.D. thesis, University of Otago.

Frishkopf, L.S., Capranica, R.R. & Goldstein, Jr., M.H. (1968). Neural coding in the bullfrog's auditory system - a teleological approach. Proceedings of the IEEE, 56, 969-980.

Ganz, L. & Wilson, P.D. (1967). Innate generalization of a form discrimination without contouring eye movements. Journal of Comparative Physiology & Psychology, 63, 258-269.

Glezer, V.D., Ivanoff, V.A. & Tscherbach, T.A. (1973). Investigation of complex and hypercomplex receptive fields of visual cortex of the cat as spatial frequency filters. Vision Research, 13, 1875-1904.

Gribbin, J. & Cherfas, J. (1982). The Monkey Puzzle. London: The Bodley Head Ltd.

Griffith, H. & Davidson, M. (1966). Long-term changes in intellect and behaviour after hemispherectomy. Journal of Neurology, Neurosurgery & Psychiatry, 29, 571-576.

Grüsser, O.J. & Grüsser-Cornehls, U. (1968). Vision Research, 8, 1173-1185. Cited in Ewert, J. (1980).Neuroethology. New York: Springer-Verlag.

Hailman, J.P. (1962). Pecking of laughing gull chicks to models of the parental head. Auk, 79, 89-98.

Hailman, J.P. (1964). Coding of the colour preference of the gull chick. Nature, 204, 710.

Hailman, J.P. (1967). The ontogeny of an instinct: the pecking response in chicks of the laughing gull (Larus atricilla, L.) and related species. Behaviour, Suppl. 15.

Hailman, J.P. (1970). Comments on the coding of releasing stimuli. In Development and evolution of behavior. (Eds.) Aronson, L.R., Tobach, E., Lehrman, D.S. & Rosenblatt, J.S. San Francisco: W.H. Freeman & Co.

Hebb, D.O. (1949). Organization of behavior. New York: John Wiley.

Heinemann, E.G. & Kadison, K. (1976). Control of pigeon's choice behavior by position of luminance of a spot of light. Bulletin of the Psychonomic Society, 7, 522-524.

Herrnstein, R.J. (1979). Acquisition, generalisation, and discrimination reversal of a natural concept. Journal of Experimental Psychology: Animal Behavior Processes, 5(2), 116-129.

Herrnstein, R.J. (1982). Stimuli and the texture of experience. Neuroscience & Biobehavioural Reviews, 6, 105-117.

Herrnstein, R.J. & deVilliers, P.A. (1980). Fish as a natural category for people and pigeons. In The Psychology of Learning and Motivation, Vol.14. (Ed.) Bower, G.H. New York: Academic Press.

Herrnstein, R.J. & Loveland, D.H. (1964). Complex visual concept in the pigeon. Science, 146, 549-551.

Herrnstein, R.J., Loveland, D.H. & Cable, C. (1976). Natural concepts in pigeons. Journal of Experimental Psychology: Animal Behavior Processes, 2(4), 285-302.

Hinton, G.E. & Anderson, J.A. (Eds.) (1981). Parallel models of associative memory. Hillsdale, N.J.: Erlbaum.

Hochberg, J. (1968). In the mind's eye. In Contemporary Theory and Research in Visual Perception. (Ed.) Haber, R.N. New York: Holt Rinehart Winston.

Hoffman, W.C. (1966). The Lie algebra of visual perception. In Journal of Mathematical Psychology, 3, 65-98.

Hoffman, W.C. (1971). Visual illusions of angle as an application of Lie transformation groups, S.I.A.M. Review, 13, 169-184.

Hoffman, W.C. (1977). An informal, historical description (with bibliography) of the 'L.T.G./N.P.' Cahiers Psychologie, 20, 135-174.

Homa, D., Sterling, S. & Trepel, L. (1981). Limitations of exemplar-based generalization and the abstraction of categorical information. Journal of Experimental Psychology: Human Learning & Memory, 7(6), 418-439.

Hubel, D.H. & Wiesel, T.N. (1962). Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. Journal of Physiology, 160, 106-154.

Hubel, D.H. & Wiesel, T.N. (1965). Receptive fields and functional architecture in two nonstriate visual areas (18 and 19) of the cat. Journal of Neurophysiology, 28, 229-289.

Hubel, D.H. & Wiesel, T.N. (1968). Receptive fields and functional architecture of monkey striate cortex. Journal of Physiology, 195, 215-243.

Hughes, H.C. (1977). Anatomical and neurobehavioral investigations concerning the thalamo-cortical organization of the rat's visual system. Journal of Comparative Neurology, 175, 311-336.

Hughes, H.C. (1982). Search for the neural mechanisms essential to basic figural synthesis in the cat. In Analysis of Visual Behavior. (Eds.) Ingle, D., Goodale, M. & Mansfield, R. Cambridge, Mass.: MIT Press.

Humphrey, N.R. (1974). Vision in a monkey without striate cortex: A case study. Perception, 3, 241-255.

Hunt, E. (1980). Intelligence as an information-processing concept. British Journal of Psychology, 71, 449-474.

Jerison, H.J. (1973). Evolution of the brain and intelligence. New York: Academic Press.

John, E.R. & Schwartz, E.L. (1978). The neurophysiology of information processing and cognition. Annual Review of Psychology, 29, 1-29.

Katz, J.J. (1972). Semantic Theory. New York: Harper & Row.

Katz, J.J. (1977). The real status of semantic representations. Linguistic Inquiry, 8(3), 559-584.

Keating, E.G. (1975). Effects of prestriate striate lesions on the monkey's ability to locate and discriminate visual forms. Experiments in Neurology, 47, 16-25.

Kellogg, R.T. (1981). Feature frequency in concept learning: What is counted? Memory & Cognition, 9(2), 157-163.

Kruglikov, R.I. (1978). [The structural and functional organization of the brain in memory processes]. Vop. Filosof., 1, 96. Cited in Shvyrkov, V.B. (1981). The unity of the physiological and the psychological in behavior. Soviet Psychology, 20(3), 36-57.

Kuhl, P.K. & Miller, J.D. (1975). Speech perception by the chinchilla: voiced-voiceless distinction in alveolar plosive consonants. Science, 190, 69-72.

Land, M.F. (1969). Structure of the retinae of the principal eyes of jumping spiders (Salticidae: Dendryphantinae) in relation to visual optics. Journal of Experimental Biology, 51, 443-470.

Lettvin, J., Maturana, H., Pitts, W. & McCulloch, W.S. (1958). What the frog's eye tells the frog's brain. Proceedingsof the I.R.E., 47, 1940-1951.

Lindsay, P.H. & Norman, D.A. (1972). Human information-processing: an introduction to psychology. New York: Academic Press.

Lubow, R.E. (1974). High-order concept formation in the pigeon. Journal of the Experimental Analysis of Behavior, 21, 475-483.

Mackintosh, J. & Sutherland, N.S. (1962). Visual discrimination by the goldfish: The orientation of rectangles. Animal Behaviour, 11(1), 135-141.

Malott, R.W. & Siddall, J.W. (1972). Acquisition of the people concept in pigeons. Psychological Reports, 31, 3-13.

Marr, D. (1976). Early processing of visual information. Philosophical Transactions of the Royal Society of London, B275, 483-524.

Martin, R.C. & Caramazza, A. (1980). Classification in well-defined and ill-defined categories: Evidence for common processing strategies. Journal of Experimental Psychology: General, 109(3), 320-353.

Medin, D.L. & Schaffer, M.M. (1978). Context theory of classification learning. Psychology Review, 85(3), 207-238.

Mervis, C.B. & Rosch, E. (1981). Categorization of natural objects. Annual Review of Psychology, 32, 89-115.

Miller, G.A. & Johnson-Laird, P.N. (1976). Language and perception. Cambridge, Mass.: Belknap Press.

Miller, G.A. & Nicely, P. (1955). An analysis of perceptual confusions among some English consonants. Journal of the Acoustical Society of America, 27, 338-353.

Moray, N. (1959). Attention in dichotic listening: Affective cues and the influence of instruction. Quarterly Journal of Experimental Psychology, 11, 56-60.

Morgan, M.J., Fitch, M.D., Holman, J.G. & Lea, S.E.G. (1976). Pigeons learn the concept of an 'A'. Perception, 5, 57-66.

Muntz, W.R.A. (1962). Effectiveness of different colors of light in releasing the positive phototactic behavior of frogs, and a possible function of the retinal projection to the diencephalon. Journal of Neurophysiology, 25, 712-720.

Muntz, W.R.A. (1963). The development of phototaxis in the frog. (Rana temporaria). Journal of Experimental Biology, 40, 371-379.

Neisser, U. (1967). Cognitive psychology. New York: Appleton-Century-Crofts.

Osherson, D.N. & Smith, E.E. (1981). On the adequacy of prototype theory as a theory of concepts. Cognition, 9, 35-58.

Pomerantz, J.P., Soyer, L.C. & Stoever, R.J. (1977). Perception of wholes and their component parts: Some configural superiority effects. Journal of Experimental Psychology: Human Perception & Performance, 3, 422-435.

Poole, J. & Lander, D.G. (1971). The pigeon's concept of pigeon. Psychonomic Science, 25, 157-158.

Premack, D. (1978). On the abstractness of human concepts: Why it would be difficult to talk to a pigeon. In Cognitive Processes in Animal Behavior. (Eds.) Hulse, S.H., Fowler, H. & Honig, W. Hillsdale, N.J.: Erlbaum.

Premack, D. (1983). Animal cognition. Annual Review of Psychology, 34, 351-362.

Ramos, A., Schwartz, E.L. & John, E.R. (1976). Evoked potential unit relationships in behaving cats. Brain Research Bulletin, 1, 69-75.

Reed, E.S. (1982). Darwin's earthworms: A Case study in evolutionary psychology. Behaviourism, 10(2), 164-185.

Reynolds, G.S. (1961). Contrast, generalization, and the process of discrimination. Journal of the Experimental Analysis of Behavior, 4, 289-294.

Robson, J.G. (1975). Receptive fields: Neural representation of the spatial and intensive attributes of the visual image. In Handbook of Perception, Vol.5, (Eds.) Carterette, E.C. & Friedman, M.P. New York: Academic Press.

Roeder, K.D. (1966). Auditory system of noctuid moths. Science, 154, 1515-1521.

Rosch, E. (1977). Human categorization. In Studies in Cross-Cultural Psychology, Vol.1. (Ed.) Warren, N. New York: Academic Press.

Rosch, E. & Lloyd, B.B. (Eds.) (1978). Cognition and Categorisation. Hillsdale, N.J.: Erlbaum.

Ryan, M.J. & Tuttle, M.D. (1981). Bat predation and the evolution of frog vocalizations in the neotropics. Science, 214, 677-678.

Ryan, M.J. & Tuttle, M.D. (1983). The ability of the frog-eating bat to discriminate among novel and potentially poisonous frog species using acoustic cues. Animal Behavior, 31, 827-833.

Schmerler, S. & Hailman, J.P. (1965). Discrimination of orientation in the Laughing Gull, Larus atricilla L. American Zoologist, 5, 655.

Sekular, R. (1974). Spatial vision. Annual Review of Psychology, 25, 195-232.

Shvyrkov, V.B. (1981). The unity of the physiological and the psychological in behavior. Soviet Psychology, 20(3), 36-57.

Siegel, R.K. & Honig, W.K. (1970). Pigeon concept formation: Successive and simultaneous acquisition. Journal of the Experimental Analysis of Behavior, 13, 385-390.

Sprague, J.M. (1966). Interaction of cortex and superior colliculus in mediation of visually guided behavior in the cat. Science, 153, 1544-1547.

Sprague, J.M., Levy, J., DiBerardino, A. & Berlucchi, G. (1977). Visual cortical areas mediating form discrimination in the cat. Journal of Comparative Neurology, 172, 441-488.

Smith, E.E. & Medin, D.L. (1981). Categories and concepts. Cambridge, Mass.: Harvard University Press.

Sutherland, N.S. (1968). Outlines of a theory of visual pattern recognition in animals and man. Proceedings of the Royal Society, B171, 297-317.

Sutherland, N.S. (1969). Shape discrimination in rat, octopus, and goldfish: A comparative study. Journal of Comparative & Physiological Psychology, 67(2), 160-176.

Sutherland, N.S. & Bowman, R. (1969). Discrimination of circles and squares with and without knobs by goldfish. Quarterly Journal of Experimental Psychology, 21, 330-338.

Tinbergen, N. (1968). Curious naturalists. New York: Doubleday & Co.

Towe, A.L. (1954). A study of figural equivalence in the pigeon. Journal of Comparative & Physiological Psychology, 47, 283-287.

Vetter, G.H. & Hearst, E. (1968). Generalization and discrimination of shape orientation in the pigeon. Journal of the Experimental Analysis of Behavior, 11, 753-765.

Watson, A. (1978). A Riemann geometric explanation of the visual illusions and figural after effects. In Formal Theories of Visual Perception. (Eds.) Leeuwenberg, E. & Buffart, H. New York: John Wiley & Sons.

Wells, M.J. (1962). Early learning in Sepia. Symposia of the Zoological Society of London, 8, 149-169.

Whitney, P. & Kellas, G. (1984). Processing category terms in context: Instantiation and the structure of semantic categories. Journal of Experimental Psychology: Learning, Memory & Cognition, 10(1), 95-103.

Wickelgren, W.A. (1981). Human learning and memory. Annual Review of Psychology, 32, 21-52.

Wilkinson, F.E. & Dodwell, P.C. (1980). Young kittens can learn complex visual pattern discriminations. Nature, 284, 258-259.

Young, J.Z. (1981). The Life of Vertebrates. 3rd ed. Oxford: Oxford University Press.

Zajaczkowska, A. (1956). Experimental determination of Luneburg's constants σ and K. Quarterly Journal of Experimental Psychology, 8, 66-78.